RULE 132 DECLARATION OF DR. RANDELL L. MILLS

I, Randell L. Mills, declare and state as follows:

1.   I am the founder and CEO of BlackLight Power, Inc., located at 493 Old Trenton Road, Cranbury, New Jersey 08512.

2.   I majored in chemistry and received my bachelor of arts degree, *summa cum laude* and Phi Beta Kappa, from Franklin & Marshall College in 1982. I received a medical degree from Harvard Medical School in 1986. While attending Harvard Medical School, I concurrently spent a year taking courses in advanced electrical engineering at the Massachusetts Institute of Technology. I have also had significant academic training in biology, chemistry, mathematics and physics.

3.   I began my research in the field of energy technology over ten years ago. I have authored, co-authored or collaborated on numerous publications, reports and presentations at scientific meetings in the field of energy technology and novel hydrogen chemistry, as shown in the attachment hereto.

4.   I am fully qualified to conduct the research that led to the discovery and development of BlackLight's lower-energy hydrogen technology.

5.   I personally conducted and/or supervised the experimental data disclosed in the articles submitted to the U.S. Patent and Trademark Office ("PTO"), which are described in the attached list. The coauthors, if any, assisted me in preparing the data.

6.   I declare further that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

By _____

Dr. Randell L. Mills

Date: _3 October 2007_____

Journal and Book Publications

116. K. Akhtar, J. Scharer, R. L. Mills, "Substantial Doppler Broadening of Atomic Hydrogen Lines in DC and Capactively Coupled RF Plasmas," IEEE Transactions on Plasma Science, submitted.

115. R.L. Mills, H. Zea, J. He, B. Dhandapani, "Water Bath Calorimetry on a Catalytic Reaction of Atomic Hydrogen," International Journal of Hydrogen Energy, in press.

114. R.L. Mills, K. Akhtar, B. Dhandapani, "Tests of Features of Field-Acceleration Models for the Extraordinary Selective H Balmer α Broadening in Certain Hydrogen Mixed Plasmas," J. Plasma Phys., submitted.

113. R.L. Mills, "Physical Solutions of the Nature of the Atom, Photon, and Their Interactions to Form Excited and Predicted Hydrino States," Physics Essay, in press.

112. R. L. Mills, J. He, Y. Lu, Z, M. Nansteel, Chang, B. Dhandapani, "Comprehensive Identification and Potential Applications of New States of Hydrogen," Int. J. Hydrogen Energy, Vol. 32, (2007), 2988–3009.

111. R. L. Mills, J. He, Z, Chang, W. Good, Y. Lu, B. Dhandapani, "Catalysis of Atomic Hydrogen to Novel Hydrogen Species H⁻(1/4) and H_2(1/4) as a New Power Source," International Journal of Hydrogen Energy, Vol. 32(13), (2007), pp. 2573–2584.

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104. R. L. Mills, Y. Lu, M. Nansteel, J. He, A. Voigt, W. Good, B. Dhandapani, "Energetic Catalyst-Hydrogen Plasma Reaction as a Potential New Energy Source," Division of Fuel Chemistry, Session: Advances in Hydrogen Energy, 228th American Chemical Society National Meeting, August 22–26, 2004, Philadelphia, PA.

103. R. L. Mills, Dhandapani, W. Good, J. He, "New States of Hydrogen Isolated from K_2CO_3 Electrolysis Gases," Chemical Engineering Science, submitted.

102. R. L. Mills, "Exact Classical Quantum Mechanical Solutions for One- through Twenty-Electron Atoms," Phys. Essays, Vol. 18, No. 3 (2005), 321–361.

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85. R. L. Mills, P. Ray, R. M. Mayo, "Highly Pumped Inverted Balmer and Lyman Populations," New Journal of Physics, submitted.

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83. R. Mills, P. Ray, M. Nansteel, R. M. Mayo, "Comparison of Water-Plasma Sources of Stationary Inverted Balmer and Lyman Populations for a CW HI Laser," J. Appl. Spectroscopy, in preparation.

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1. R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, April 2007 Edition posted at www.blacklightpower.com

Book Publications

10.   R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, December 2006 Edition, BlackLight Power, Inc., Cranbury, New Jersey, Available at www.blacklightpower.com.

9. R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, June 2006 Edition, BlackLight Power, Inc., Cranbury, New Jersey

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Substantial Doppler broadening of atomic-hydrogen lines in DC and capacitively coupled RF plasmas

Kamran Akhtar[1], John E. Scharer[2], and Randell L. Mills[1]

[1] BlackLight Power, Incorporated
493 Old Trenton Road, Cranbury, New Jersey 08512

[2] Department of Electrical and Computer Engineering
University of Wisconsin-Madison, Wisconsin 53706

The mechanism of extraordinary broadening of the Balmer lines of hydrogen admixed with Ar or He as opposed to Xe in a DC glow discharge and a capacitively coupled rf discharge is studied over a wide range of pressure and gas compositions. High-resolution optical emission spectroscopy is performed parallel to the electrode axis (end-on) and perpendicular to the electrode axis (side-on) along with Langmuir probe measurements of plasma density and electron temperature for the capacitive discharge case. An excessively broad and symmetric (Gaussian) Balmer emission line corresponding to 20-60 eV of hydrogen atom energy is observed in Ar/H_2 and He/H_2 plasmas when compared to the majority species atom temperatures. Energy is transferred selectively to hydrogen atoms whereas the atoms of admixed He and Ar gases remain cold (<0.5 eV). In the field acceleration model that has recently been put forth to explain the broadening [Cvetanovic et. al. J. App. Phys., Vol. 97, 033302-1, 2005], there is neither a preferred ion nor atom and according to this model, one should observe enhanced temperature hydrogen and helium atoms in He/H_2 discharges where the atomic mass is more comparable (4:1). The absence of hot H atoms in Xe/H_2 plasmas also challenges the paradigm of the field acceleration model since Xe is also a noble gas and electronically similar to He. The model of an energetic chemical reaction of hydrogen [Mills et. al IEEE Trans. Plasma Sci., 31, p.338, 2003] as the source of broadening can explain the observation that only the selective heating of hydrogen atoms in certain plasmas exhibits the selective extraordinary broadening and isotropic emission profiles.

I. INTRODUCTION

Substantial Doppler broadening of hydrogen Balmer lines has been observed in pure hydrogen and specific gaseous mixtures of hydrogen with certain heavier atom plasmas produced by DC and capacitively coupled 13.56 MHz radio frequency waves [1-17]. This broadening is caused by the presence of excited hydrogen atoms. In all these instances, energy is transferred selectively to the hydrogen atom whereas the H_2 molecules as well as the He and Ar atoms remain cold. Historically, most mechanisms proposed for excessive H_α broadening in pure hydrogen and mixtures of hydrogen with inert gases [1-14] are explained in terms of energetic ions (H^+, H_2^+ and H_3^+) that are accelerated in the cathode fall region followed by energy transfer to the matrix gas (H and H_2) through charge exchange collisions. However, there are variations in the proposed theoretical explanations of the mechanisms that provide energy to atomic H and cause the observed enhanced blue-shifted H_α spectra width that is symmetric with respect to the red-shifted portion of the emission profile. It should be noted, however, that none of these mechanisms explains the selective transfer of energy to the hydrogen atomic state with the atoms of the admixed gases remaining cold (<0.5 eV).

In a pure hydrogen discharge, the Doppler-broadened profile exhibits the presence of a bimodal (or a tri-modal) distribution of neutral species temperatures [14]. The profile consists of a central peak that corresponds to slow thermal hydrogen atoms with kinetic energies in the range 0.25 to 1.0 eV. The population of warm H atoms (10-20 eV) is evident in the plateau of the Doppler broadened profile along with a population of fast hydrogen atoms (> 40 eV). There is general agreement on the mechanisms proposed for the production of slow H (~0.1-1.0 eV) atoms in the excited n=3 state through the process of dissociative excitation, $H_2 + e^- \rightarrow H_2^* + e^- \rightarrow H^*(n=3) + H$, and dissociative ionization,

$H_2 + e^- \rightarrow 2e^- + H_2^+ \rightarrow H^*(n=3) + H^+$, of hydrogen molecules and electron impact excitation of H atoms, $H + e^- \rightarrow e^- + H^*(n=3)$ [1-2].

There are significant variations in the literature describing the mechanisms proposed to explain the production of hydrogen atoms with energies greater than 20 eV. These were originally proposed to be the result of dissociation of H_2^+ ions in vibrationally excited molecular ground states [2-3]. Recently, the mechanism of charge exchange between ions accelerated in the sheath and neutrals and ion impact on electrodes has been proposed as the source of energetic hydrogen atoms in these discharges. In this model, henceforth called the Collisional Model (CM) [5 and references therein], sheath accelerated H^+ and H_3^+ ions in a hydrogen plasma are proposed to either transfer charge directly to the hydrogen atom or dissociate the H_2 molecule followed by charge exchange collisions to explain the energy spectrum of hydrogen atoms [1-15]. The processes are governed by the following reactions [5-7] where the * indicates excited n=3 atomic state:

$$(H^+)_{fast} + H_{slow} \rightarrow H^*_{fast} + (H^+)_{slow} \qquad (1)$$

$$(H^+)_{fast} + (H_2)_{slow} \rightarrow H^*_{fast} + (H_2^+)_{slow} \qquad (2)$$

$$(H_3^+)_{fast} + H_{slow} \rightarrow H_3 + H^*_{fast} + (H_2^+)_{slow} \qquad (3)$$

$$(H_3^+)_{fast} + (H_2)_{slow} \rightarrow H^*_{fast} + (H_2)_{fast} + (H_2^+)_{slow} . \qquad (4)$$

Since the particle acceleration due to the electric field is directional, the energy gained by a positive ion as it travels towards the cathode will maintain that directionality along with the directed energy of the excited hydrogen atom as long as ion-neutral collision rates are small. This mechanism can only account for the red portion of the spectrum when viewed optically towards the ion accelerating electrode sheath. The observed symmetry in the Gaussian profile of the

hydrogen Balmer line is explained in terms of the sputtered fast H atoms and the back-reflected fast H atoms from the cathode surface [5]. It is argued that this will give rise to a symmetric distribution of energetic H atoms leaving the cathode compared to those accelerating towards the cathode.

In the presence of inert gases, the additional process of charge transfer has been proposed to explain the symmetric H_α broadening [3,12-13]. The introduction of Ar in a pure H_2 plasma increases the Balmer line emission intensity that implies that the concentration of excited hydrogen atoms in the excited n=3 state is also increased. In addition, the fractional population of hot hydrogen atoms obtained from the area under the Gaussian curve implies a concentration in excess of 80 percent of the population in the n=3 state. It has been suggested in the above articles that energetic Ar^+ ions dissociate and ionize H_2 to form ArH^+ that enhances the population of H_3^+ that is proposed as the primary source of atomic hydrogen as shown below when Eq. (6) is combined with Eq. (4).

$$Ar^+ + H_2 \rightarrow ArH^+ + H \tag{5}$$

$$ArH^+ + H_2 \rightarrow H_3^+ + Ar \tag{6}$$

The role of metastable argon ions in the enhanced production of H_3^+ ions through the formation of molecular hydrogen ions has also been emphasized [6].

$$Ar^+(3p^{5\,2}p_{1/2}^0) + H_2 \rightarrow Ar + H_2^+ \tag{7}$$

$$H_2^+ + H_2^+ \rightarrow H_3^+ + H \tag{8}$$

It has been suggested in the above articles that the contribution of these pathways to the significant production of H_3^+ in Ar/H₂ results in an enhanced population of energetic H_{fast} atoms through the processes described in Eqns. (3-4).

However, some of the recent observations [17-26] in DC and capacitively coupled rf discharges are in contrast to the field acceleration based Collisional Models described earlier. For example, it is important to note that, to the best of our search of the scientific literature, no experimental observation has ever been reported, including results in this paper where equally energetic atoms of admixed gases have been found even when the plasma is collisional and mass ratios are comparable. The energy is transferred selectively only to the hydrogen atom whereas the electron energy is less than few eV and admixed gas atoms remain cold (<0.5 eV). It is also very intriguing that no hot H atoms are observed when the admixed gas is xenon. In the CM, the energy of the hot H atom should be independent of the nature of the background gases except for differing collision cross-sections with the background gas. Therefore, it is not possible to readily explain the presence of broadening in argon/hydrogen and helium/hydrogen plasmas along with the absence of broadening in xenon/hydrogen plasmas using this model. In addition, the observation of comparably hot hydrogen atoms in regions outside the plasma sheath requires the local creation of energetic H atoms. As discussed later, the rapid thermalization of H atoms with the background gas due to short ion-neutral collision mean free paths should also confine fast H near the region where it is formed. Therefore, only a process where hot H is produced locally can explain the comparable energies of hot H observed well outside the plasma sheath regions.

It should be noted however, that these observations demonstrate that the source of these hot H atoms is a process fully consistent with the Mills' model of energy production known as Resonance Transfer Model (RTM) [17-26]. The RTM predicts excessive broadening due to a novel energetic chemical reaction of H with certain catalysts involving a two-step energy transfer. First, resonant energy transfer occurs from H to a catalyst and then a second radiative emission or a resonant energy transfer to another H atom that serves as a third body to take away

the remaining reaction energy [19-20]. In this model, it is postulated that the electron in the hydrogen atom that undergoes a 'catalytic' reaction that allows decay from the 'conventional' ground state (principal quantum number, $n=1$) to a 'fractional' quantum state (e.g. $n=1/2$). Since the ionization energy of hydrogen is 13.6 eV, two hydrogen atoms can also provide a net enthalpy equal to the potential energy of the hydrogen atom, 27.2 eV— the necessary resonance energy, for a third hydrogen atom to form H ($n=1/2$).

In order to clarify the underlying mechanism of hydrogen Balmer alpha broadening in hydrogen plasmas and plasmas of hydrogen admixed with noble gases and test the validity of field acceleration based Collisional Model (CM) [5], a comprehensive experiment that covers a wide range of gas pressure and plasma parameters has been performed. A DC glow discharge with pin electrodes and a capacitively coupled radio frequency plasma over a wide pressure range (three orders of magnitude – 10 mTorr to 10 Torr) along with different gas mixture ratios are used to test the ability of the CM to explain the unusual nature of the observed hydrogen broadening. As suggested by the CM, the degree of symmetry of the plasma emission profile should be a function of the electron-neutral and ion-neutral collision frequency and, therefore, should depend on the neutral gas pressure. The CM mandates that observations parallel and perpendicular to the electric field lines yield different emission profiles if the collisional scattering rate is sufficiently small. The experimental setup allows observations both parallel and perpendicular to the electrode axes to test this property. In addition, the presence of hot H atoms was examined in regions far away from the high electric field plasma sheath region near the electrodes. The CM also implies that the energy of hot H atoms is independent of the nature of admixed gases. In contrast, the RTM proposes that the nature of admixed gases will be critical to the broadening mechanism that results in the observed hydrogen emission profile. This aspect is

tested by mixing different gases with hydrogen and observing broadening in the plasma emission profile. In addition to plasma emission spectroscopy, a Langmuir probe is also used to diagnose the capacitive discharge plasma. It should be noted here that the experiments were designed and parameter regimes were considered primarily to test the field acceleration based Collisional Model (CM). In this process, however, the Resonance Transfer Model (RTM) is also tested in light of these new observations.

II.   EXPERIMENTAL SYSTEM

The experimental arrangement of the DC discharge is shown in Figure 1. In this configuration, the discharge is created between fine tips of 2% thoriated tungsten electrodes of diameter 1/8 inch spaced 2 cm apart inside either a ½ inch or 1 inch diameter quartz tube. Very fine electrode tips (Fig.1) that are tapered over the last ½ inch to a point are used to minimize the surface area perpendicular to the face of the electrodes. The high E-field near the sharp electrode tip will reduce rapidly as one moves away from it. High-resolution plasma emission spectroscopy is performed through an annulus parallel to the electrode axis along the electric field lines (end-on) and perpendicular to the field lines (side-on). For the end-on observation, plasma emission can be sampled looking towards the anode or cathode. For the side-on observation, an axial scan of the plasma emission is observed in a region adjacent to the cathode rod. Here the cathode tip is located at z=0 cm. The DC plasma setup is placed on an X-Y motion table so that an accurate axial measurement can be carried out without changing the position of the fiber optic bundle. The discharge pressure is maintained in the range of 10 mTorr to 10 Torr. A stabilized negative DC power supply (Kaiser System Inc., Beverly, MA) with voltage and current in the range 0-2000 V and 0-500 mA, respectively, is used to create the plasma. A high

7

wattage ballast resistor of 20 kΩ is used in series with the power supply to limit the discharge current. Once the discharge is created, the glow discharge is maintained with cathode-anode voltages of 300-400 volts and results in discharge currents in the range of 10-100 mA depending upon the gas pressure, gas flow and discharge configuration.

The capacitively driven radio frequency plasma system consists of a large cylindrical (14 cm ID × 36 cm length) quartz plasma chamber with two electrodes (stainless steel plates of diameter 8.25 cm) placed 1 cm apart at the center (Figure 2). Radio frequency power (13.56 MHz, RF Power Products Inc. NJ, Model RF 5, 500 Watts) is coupled to the electrode using a commercially available impedance matching network (RF VII Inc., Glassboro, NJ). Radio frequency power from the source is fed through the impedance matchbox to the capacitive electrodes using a 1/2-inch diameter steel tube that also facilitates the end-on (parallel to the electric field) observation of plasma through holes in the center of the electrodes. One of the electrodes is permanently grounded. A common ground is maintained for the grounded electrode, rf shield and vacuum system. Two ports in the center of the plasma chamber (Position 2) permit side-on observations of plasma emission 90° and 45° to the electric field. Another side port at the same position allows insertion of a Langmuir probe for plasma density and electron temperature measurements. Plasma emission far away (15 cm) from the high-field plasma sheath region is sampled at Positions 1 and 2. In order to ensure that the plasma emission sampled at positions 1 and 2 have no contribution from the reflected light, the inside of the rf shield enclosure is made non-reflecting.

A helium leak detector (QualyTest, Model: HLT 260, Pfeiffer Vacuum) is utilized to leak test the evacuated plasma chamber. The plasma chamber is maintained with a leak rate below 10^{-7} Torr-L/s. Independent mass flow controllers (MKS) were used to introduce UHP grade

(99.999%) H_2, Ar, He and Xe gases into the plasma chamber through Ultratorr fittings at one end. The chamber pressure for all gas compositions is maintained between 10 mTorr and 10 Torr. An MKS Baratron gauge is used to read the chamber pressure.

III.   DIAGNOSTICS

A.   Plasma Emission Spectroscopy

Plasma emission from the glow discharge passes through a high-quality UV (200-800 nm) fiber-optic bundle into a monochromator through a 220F matching fiber adapter that is detected either by a photomultiplier tube (PMT) with a stand-alone power supply of 995 volts or by a high quality scientific grade liquid nitrogen cooled CCD arrays. The numerical aperture of the fiber optic bundle is 0.12 and the corresponding acceptance angle is 12^0. The spectrometer utilizes a 1250 mm focal length spectrometer (Jobin Yvon Horiba: Model 1250M Research Spectrometer) with a 2400 g/mm grating and a high resolution of $\pm$ 0.006 nm. The spectrometer is rated for an accuracy of ± 0.05 nm and repeatability of ± 0.005 nm. The spectrometer was scanned through emission profiles of Balmer lines with a step size of 0.01 nm. The entrance and exit slits were set at 20 µm. The liquid nitrogen cooled Symphony model CCD detectors are a family of array detectors from Jobin Yvon with 16 bit ADC with 20 KHz and 1 MHz read out. A back illuminated 2048x512 CCD of 13.5 µm $\times$ 13.5 µm size provides very high-resolution capability.

The Doppler-broadened line shapes for atomic hydrogen have been used to calculate the energy of the atomic hydrogen. The motion of a radiating particle moving towards or away from an observer results in a wavelength shift of the emitted line. This broadening is related to the random thermal motion of the emitting atoms and for a Maxwellian velocity distribution it

depends only on the translational (kinetic) temperature. Full half-width, $\Delta\lambda_G$, of the Gaussian profile results from the Doppler ($\Delta\lambda_D$) and instrumental ($\Delta\lambda_I$) half-widths are $\Delta\lambda_G = \sqrt{\Delta\lambda_D^2 + \Delta\lambda_I^2}$. The instrumental half-width $\Delta\lambda_I$ is 0.006 nm and is negligible. The temperature of atomic hydrogen in terms of Doppler ($\Delta\lambda_D$) half-width is given as [27]

$$\Delta\lambda_D = 7.16 \times 10^{-7}\lambda_0 \left(\frac{T}{\mu}\right)^{1/2} \text{ nm.}$$

Here λ_0 is the line wavelength in nm, T is the temperature in K, and μ is atomic mass number(=1 for hydrogen). It can be seen that Doppler broadening is more pronounced for lighter elements at high temperatures. For high densities $>10^{13}$/cc, Doppler broadening competes with Stark broadening. In addition, a contribution to the broadened profile may arise from the mass motion of the plasma. However, for these glow discharges where the plasma density is low ($<10^{11}$/cc), the contribution of Stark broadening to the line shape profile can be neglected without loss of accuracy. We checked the contribution from the mass motion of the plasma by sampling the plasma emission side-on as well as end-on. The absence of line shift shows that the line broadening is primarily due to the thermal motion. In each case, the error in the average Doppler half-width over 10 scans was about ±5% that is attributed to the fluctuations in the plasma. The half-width of the Doppler broadened emission profile was obtained using a multi-Gaussian curve fit utilizing the curve fitting software GRAMS from Jobin Yvon Horiba.

B.   Plasma Density Measurement

In the present work, Langmuir probe (LP) data has been used for obtaining the bulk plasma density and bulk electron temperature in the capacitive discharge [28-29]. The cylindrical Langmuir probe is a tungsten tip of radius 1 mm and length 5 mm enclosed in an alumina tube.

The LP is placed between the electrodes at position 2 where most of the plasma heating occurs. In order to characterize the capacitively coupled radio frequency plasma, an rf compensated LP is utilized that allows accurate measurement of bulk electron temperature. The probe filtering does not allow time varying, non-Maxwellian properties of the electron energy distribution to be readily observed. Thus, the possible presence of a small population of hot electrons ($E_c > 20$ eV) in such low-density capacitive discharges at gas pressures above 10 mTorr is not considered in this paper. Data acquisition software written in Lab View is used for automatic transfer from the oscilloscope to the computer. The entire LP data analysis in the present work was undertaken using an interactive graphics based software package developed in MatLab.

IV. EXPERIMENTAL RESULTS

A. DC Discharge

The axial profile of the Balmer H_α line (near 656.3 nm) observed perpendicular (side-on) and parallel to the electrode axis (end-on) looking towards anode as well as cathode is obtained for 1 Torr of Ar/H_2 (95/5%), He /H_2 (95/5%), and Xe/H_2 (95/5%) 300-400 V DC plasmas produced between fine tipped electrodes spaced 2 cm apart. The DC discharge is produced over a wide pressure range (and ion mean free path) of 10 mTorr-10 Torr. Significant broadening was observed for Ar/H_2 and He/H_2 plasmas whereas no broadening was observed for Xe/H_2 plasmas.

Axial profiles of the H_α line for side-on as well as for end-on observations for 1 Torr argon mixed with 5% hydrogen plasma are shown in Fig. 3 and Fig. 4, respectively. The emission profile is isotropic and symmetric. The axial scan is performed parallel to the cathode pin axis with the tip located at z=0. The fiber optic cable entrance aperture is placed perpendicular to the surface of the quartz tube. The sampled plasma volume with an acceptance

11

angle of 12^0 for 1 inch and ½ inch diameter tubes is 30 mm^3 and 4 mm^3, respectively. The H_α line profiles clearly exhibit a two-component Doppler-broadened profile corresponding to two populations of hydrogen atoms. The central narrow part corresponds to slow hydrogen atoms with temperatures in the range of 0.4-0.5 eV. The broad component of the profile corresponds to fast hydrogen atoms with an average temperature of ~ 40 eV. The fractional concentration of the slow part as obtained by curve fitting is 20-25% and the fast hydrogen component corresponds to 80-75 % indicating that the production of fast hydrogen atoms is substantial. Similar emission profiles are obtained for He/H$_2$ plasmas where the fast hydrogen atoms have temperatures in the range of 30-40 eV. In contrast, only the slow component (~0.5 eV) of the hydrogen population is observed for Xe/H$_2$ plasmas (Fig. 5). The axial temperature and population profiles of both fast and slow hydrogen atoms corresponding to the emission profiles in Fig.3 are shown in Fig. 6. It can also be seen from Figs. 3 and 6 that the average width of the two Gaussians of the Doppler broadened profile and hence the average temperature does not change appreciably along the axis. Even though the potential drops primarily near the cathode tip, the population of fast hydrogen atoms (area under the curve) peaks at a distance 2 cm away from the cathode tip. Moreover, the population of fast hydrogen atoms as a fraction of the total population is a minimum (82%) at the cathode tip (z=0) and it increases to 94% at z = 2 cm and remains nearly uniform up to z = 8 cm (Fig. 6). It is noted that the intensity and corresponding plasma density decreases away from the cathode tip (Fig. 3) although the hot hydrogen component increases.

Figure 7 shows the normalized emission profile for an end-on observation in Ar/H$_2$ and He/H$_2$ plasmas looking towards the anode. A similar symmetrical emission profile is also obtained when the emission is sampled looking towards the cathode. Reflection of field-accelerated ions in equal measure to the accelerated direction is required by the CM to explain

the absence of either a predominant red or blue wing in the emission profile for the end-on observation. Furthermore, the symmetrical profile cannot be explained by the gas matrix collision effect as no change in the normalized profile symmetry is observed as the gas pressure is varied from 10 mTorr to 10 Torr resulting in a variation of electron-neutral collision frequency by three orders of magnitude (Fig. 8).

The average thermal energy of hot hydrogen atoms as catalytic (Ar, He) and non-catalytic (Xe) gases are added to a 100 mTorr hydrogen plasma DC discharge is shown in Fig. 9. As the fractional concentration of the catalyst gas is increased, the thermal energy of hot hydrogen atoms increases. In contrast, the hot H atom thermal energy decreases sharply with increasing Xe concentration. The absence of H_α broadening with a non-catalyst such as Xe cannot be explained on the basis of the collisional model since the acceleration mechanism should be independent of the ion mass.

In addition, the transfer of energy from the electric field in these admixed plasmas is selectively to hydrogen atoms. Since the mass ratio of He to atomic hydrogen is 4:1, especially for highly collisional plasmas at higher gas pressures, it is expected from the Collisional Model [5] that a correspondingly energetic concentration of helium atoms (Doppler broadened profile) will be present. The Doppler half-width of the 667.82 nm He I line as shown in Fig. 10 is 0.012 nm and it can be accurately resolved by the high-resolution spectrometer with an instrumental half-width of only 0.006 nm. The He atoms' average thermal energy corresponding to a 0.012 nm Doppler half-width is 0.2 eV. No change in Doppler broadening of the 667.82 nm He I line was observed for all pressure and composition ranges studied in these experiments. The absence of hot helium atoms in He/H_2 plasmas where the hydrogen atoms have 30-40 eV energies also contradicts the Collisional Model because the atomic mass ratios are comparable (4:1).

13

B.   Capacitively Coupled RF Discharge

The capacitively coupled radio frequency discharge is characterized using Langmuir probe (LP) and plasma emission spectroscopy diagnostics. The LP is employed to measure electron bulk plasma density (n_e) and electron temperature (T_e) and to determine if a bulk population of high temperature (>5 eV) electrons, not detectable by spectroscopic techniques, exists in our capacitively coupled RF plasmas. A side port at position 2 (Fig. 2) allows the insertion of the LP between the rf electrodes. The on-axis LP measurements are summarized in Table 1 for different noble gases admixed with 10% hydrogen at constant pressure of 100 mTorr. The coupled radio frequency power is maintained constant at 100 W for all the cases. In general, a low-density plasma ($\sim10^{10}$ cm^{-3}) with bulk electron temperatures of 2-3 eV is observed for all plasma conditions. There is a slight drop ($\sim$15-20%) in n_e as well as in T_e as hydrogen is added to the pure noble gas plasmas. It should be noted, however, that we did not observe any high-energy (>5 eV) electron population obtained from the LP measurements. A single temperature bulk electron population characterizes these plasmas. The absence of higher-energy electrons in the higher-field regions between the electrode plates implies that there also are no fast electrons in low field regions far away from the electrodes.

Plasma emission from capacitively coupled rf discharges varied over a wide pressure range is sampled perpendicular to the electric field between the large disc electrodes (Position 2 in Fig. 2) and along the electric field through the 1 cm holes in the electrode plates (end-on). In addition, observations are also made at locations far way from the electrode plates (Positions 1 and 3 in Fig. 2). Isotropic and symmetric H_α line profiles are observed for all three locations, independent of the observation angle relative to the electric field direction. The line profile also

14

remains symmetric as the gas pressure is varied over a wide range from 10 mTorr to 10 Torr. Line broadening is observed only for Ar/H_2 and He/H_2 plasmas and there is no broadening in comparable control mixtures of Xe/H_2. The energy of the hot H atoms increases with increasing concentration of Ar and He gases whereas it decreases with Xe concentration. For the Ar/H_2 and He/H_2 plasmas the energy is selectively transferred to hydrogen atoms. In addition, the temperature of fast H atoms is quite uniform throughout the plasma chamber.

The average thermal energy of hot hydrogen atoms as a function of Ar, He and Xe concentrations [H_2(x sccm); Ar, He, Xe (y=1-x sccm)] is shown in Fig. 11. A pure hydrogen plasma at 150 mTorr with a 20 sccm flow rate is produced at a coupled rf power level of 200 W. The corresponding thermal energy of the fast hydrogen atoms in this hydrogen plasma is ~ 13-15 eV. Noble gases are introduced into the plasma chamber and the total chamber pressure and flow rate are maintained at 150 mTorr and 20 sccm, respectively, by adjusting the hydrogen and noble gas flow rates. As shown in Fig. 11, the average thermal energy of the hydrogen atom, obtained from symmetric emission profiles, increases from ~13-15 eV to 25-30 eV as the Ar and He fraction is increased. In contrast, the average energy of the hydrogen atom decreases with increasing concentration of Xe.

Figures 12 and 13 show the energy and fractional population of fast hydrogen atoms in Ar/H_2 (95/5%) plasmas as the chamber pressure is varied from 10 mTorr to 10 Torr. Plasma emission is sampled perpendicular to the field between the electrodes and along the field lines through holes in the powered and grounded electrodes. As shown in the figures, the fast hydrogen energy (20-25 eV) and their fractional population (70-80%) in n=3 states remains nearly constant as the gas pressure is varied over three orders of magnitude. Very similar profiles

15

of fast hydrogen energy (Fig. 14) and fractional population (Fig.15) as a function of pressure are obtained for (95/5%) He/H$_2$ plasmas.

The presence of hot hydrogen far away from the high field sheath region is in contradiction with the Collisional Model. The plasma emission is sampled at Position 1 and Position 3 (Fig. 2) and angular variation is obtained by rotating the optical probe. The reference is normal to the chamber axis and as the observation angle is varied, plasma emission far away (~ 6 cm) from the electrode region is sampled. As shown in Fig. 16, there is a very small influence of the tilt angle on the hot hydrogen energy for both Ar/H$_2$ and He/H$_2$ plasmas. It should be noted here that the symmetry of the emission profile is independent of the angle of observation.

V   DISCUSSION

The observations and implications resulting from this study contradict the Collisional Model [5] where excessive H$_\alpha$ broadening in pure hydrogen and mixtures of hydrogen with noble gases is explained primarily in terms of energetic ions (H$^+$, H$_2^+$ and H$_3^+$) accelerated in the cathode fall region followed by energy transfer to the matrix gas (H and H$_2$) through charge exchange collisions. The character of atomic hydrogen broadening, namely the fast component temperature and the fractional population of the fast hydrogen atoms is quite different for different gas mixtures. In all variations of the collisional model [5], one consistent aspect is that the energy required for selective heating of the hydrogen atoms in plasmas consisting of hydrogen and hydrogen admixed with other gases is locally absorbed by ions from the electric field in the cathode fall region. In the CM at low pressures and collisionality, the emission profile should be dependent on the observation angle relative to the electric field direction. In order to explain the observed symmetry in the emission profile, they have argued that sputtered fast H

16

atoms and the back-reflected fast H atoms from the cathode surface give rise to fast H concentrations leaving the cathode in the same abundance as that moving towards the cathode.

We summarize the significant results of our experimental observations that are inconsistent with the field acceleration based Collisional Model [5]: 1) Hot hydrogen atoms are observed only for pure hydrogen and specific mixtures such as Ar/H_2 and He/H_2 plasmas whereas no hot H atoms are found when hydrogen is admixed with electronically similar Xe [36]. 2) In the Ar/H_2 and He/H_2 cases, energy is transferred selectively to hydrogen atoms where molecular hydrogen and the admixed gas atoms remain colder (<0.5 eV). 3) The population of neutral H atoms is much hotter (15-40 eV) than any of the charged species ($T_e \sim$ 2-3 eV in capacitive discharge). 4) The emission profile is symmetric over a wide pressure and mean free path range (three orders of magnitude) and is independent of the observation angle relative to the electric field direction. 5) Comparably hot hydrogen atoms are observed in field-free regions far away (up to 15 cm) from the high-field sheath region. In the following sections we discuss the inconsistency of the field acceleration based Collisional Model to account for these results and demonstrate that the Resonance Transfer Model is consistent with these observations.

Let us consider the presence of hot hydrogen atoms that occur only for pure hydrogen and hydrogen admixed with Ar and He plasmas and the absence of hot hydrogen atoms in electronically similar Xe/H_2 plasmas for the entire pressure range from 10 mTorr to 10 Torr. In the field acceleration based Collisional Model, the energy of hot hydrogen atoms should be independent of the nature of the electronically similar background gas except for differing collision cross sections of their ions with H. In order to test the collisional effect of background gases, we consider the cross section data for Balmer alpha and beta line emission from H and H^+ impact reactions on hydrogen (H_2) and our other reacting gases [31-36]. It should be noted that

cross-section data for low energy (< 100 eV) H and H^+ impact on all three reacting gases considered in this paper are not available. Therefore, H_α emission cross-sections from the impact of 100 eV H atoms on noble gas targets $H + X (X = Ar, He, Xe) \rightarrow H_\alpha$ are considered. These are 7×10^{-17} cm^2, 2×10^{-18} cm^2, and 5×10^{-18} cm^2 for Ar, He, and Xe, respectively, [31,33,35]. Similarly, the H_α emission cross-sections from 100 eV H^+ impact $H^+ + X (X = Ar, Xe) \rightarrow H_\alpha$, are 2×10^{-19} cm^2 and 1×10^{-17} cm^2 for Ar and Xe, respectively [32,36]. The emission cross-section data for $H^+ + He \rightarrow H_\alpha$ reaction is not available for H^+ energies below 1.25 keV because of the small magnitude of the photon signals [36]. The cross section for $H^+ + He \rightarrow H_\alpha$ collisions at H^+ energies of 1.25 keV is given as $0.6 \pm 0.3 \times 10^{-20}$ cm^2 and it will be much smaller for lower H^+ energies [36].

The CM argues that H^+ ions will travel and be accelerated over longer distances and gain more energy before interacting with the target gas if the cross-section of H^+ impact on the target gas is smaller. As a result, increasingly energetic H^+ ions and, therefore via charge exchange, more energetic H atoms should be observed when the target gas is changed from Xe to Ar to He. Hence, following these arguments, we should observe the most energetic H atoms in the presence of He gas at low pressure. In addition, the H_α emission intensity should be similar for both He and Xe since the H impact cross-sections on He and Xe are similar. However, we observe H atoms of comparable energy (30-40 eV in the DC discharge and 20-25 eV in the capacitive discharge) with either He or Ar as the background gas whereas the H atom energies are only 1-2 eV with Xe. The H_α line intensity is also sharply reduced in Xe/H$_2$ discharges indicating low atomic hydrogen concentrations in non-RT plasmas. It can be concluded,

therefore, that the collisional model fails to explain the absence of fast H in Xe/H$_2$ discharges in contrast to its presence in Ar/H$_2$ and He/H$_2$ discharges.

These observations are consistent with the RTM which mandates that hot hydrogen atoms will be observed in Resonance Transfer (RT) plasmas where an ion is present that can provide a net enthalpy of reaction of an integer multiple of the potential energy of atomic hydrogen. Hence He$^+$, and Ar$^+$ can act as 'catalysts' for the process since the electron ionization energies are an integral multiple of 27.2 eV [24]. Furthermore, as predicted by the RTM, Xe species are incapable of acting as catalysts since the ionization energy for Xe is not an integral multiple of 27.2 eV. As a result we do not observe hot hydrogen atoms in Xe/H$_2$ plasmas. In addition, the atomic hydrogen concentrations in non-RT plasmas are also low as evidenced by the emission line intensity.

We now consider the observation that the energy is transferred selectively primarily to hydrogen atoms (15-40 eV) whereas the atoms of admixed gases remain cold (<0.5 eV). In the Collisional Model there are neither preferred ions nor atoms and, therefore, one should observe correspondingly hot atoms of the admixed gases along with the hot hydrogen atoms. To our knowledge, no measurement has ever been made where equally hot atoms of admixed gases have been found. In collision dominated plasmas at higher gas pressures where an ion is bound to suffer many collisions with the background gas as it moves towards the cathode and where the mass ratios of the constituent gases are comparable, the presence of correspondingly hot atoms of admixed gases is inferred from the Collisional Model. Let us consider a He/H$_2$ plasma at 10 Torr with the electron-neutral collision frequency of 3×10^{10} s^{-1} [30]. If in gas mixtures where only a trace amount of hydrogen (~1%) is added to the helium plasma, plasma hydrogen and helium ions will undergo many collisions with the background helium gas as they travel towards

cathode. It should be noted that the recombination rate coefficients of helium and hydrogen ions with energy in the range $\approx$ 20-30 eV is given by the reaction $He^+ + e \rightarrow He$ and $H^+ + e \rightarrow H$. The two-body recombination rates for these two processes are comparable ($\alpha_e = 10^{-13}$ cm^3/s) [37-38]. Therefore, the survival probability of both He$^+$ and H$^+$ ions as they travel towards the cathode is comparable. It should be noted, however, that with an atomic mass ratio of 4:1 in helium-atomic hydrogen plasmas, we observe hydrogen atoms with average energies of 30-40 eV whereas helium atoms are cold and have energies less than 0.5 eV (Fig. 10). In contrast, this selective transfer of energy to hydrogen atoms even though other comparable mass ratio ions are present is a cornerstone of the RTM prediction.

As shown in Fig. 16, there is a significant presence of comparably hot hydrogen atoms far away from the high-field plasma sheath regions where most of the potential variation occurs. It is well known that outside the sheath region, where the plasma is largely quasi-neutral, the plasma potential variation is very small. Therefore, in a field free region, the field acceleration CM cannot explain the existence of hot hydrogen up to 15 cm from the electrode. In order to explain the presence of hot H atoms in low field regions, the modified CM [5] requires the presence of fast electrons that produce hot atomic hydrogen with an energy comparable in magnitude to that obtained in the high field region where the source of these atoms are accelerated ions in the sheath. The measured electron temperature using the Langmuir probe located between the rf plates, where most of the electron heating takes place, is $\approx$ 2-3 eV (Table 1). It is reasonable, therefore, to argue that the bulk of the plasma well away from the electrodes region is cold. Moreover, the tail of the electron energy distribution function comprising high-energy electrons is not observed in the LP measurements for up to $-$ 70 V applied voltages and is definitely negligible in the region far away from the electrodes. Hence, these electrons cannot

produce energetic ions that recombine to form H atoms with energies > 15-20 eV. The cross

sections for resonant charge exchange transfer ($Ar^+_{fast} + Ar_{slow} \rightarrow Ar_{fast} + Ar^+_{slow}$

and $He^+_{fast} + He_{slow} \rightarrow He_{fast} + He^+_{slow}$) can be utilized to estimate the distance traveled by an ion

produced in the cathode fall region without suffering a charge exchange collision that reduces the

maximum energy it can obtain. At 20 eV, the resonant charge exchange transfer cross sections

(σ_i) for Ar and He ions are comparable at 2.2×10^{-15} cm^2 and 1.5×10^{-15} cm^2, respectively [39].

The mean free path is given as $\lambda_i = \dfrac{1}{n_g \sigma_i}$ cm, where n_g, the neutral particle density, is a function

of gas pressure. At 10 mTorr, the mean-free path for charge transfer, λ_i, is 0.06 cm. Therefore,

the ions produced in the cathode fall region will not maintain their energy over a distance of 15

cm without suffering a charge exchange collision in these plasmas [39]. These ions cannot be the

source of hot H atoms in a region far away from the electrodes. Moreover, the radiative lifetime

of the hydrogen n=3 state is 10^{-8} s [15] and with an assumed average velocity of 10^6-10^7 cm/s

corresponding to hydrogen energies of 1-100 eV, it can only travel a distance of 0.01-0.1 mm

before emission and reduced energy. This implies that the observed H$_\alpha$ emission is a result of

local excitation. The rapid thermalization of H atoms with the background gas will also localize

fast H concentrations to the region where it is formed. Therefore, a mechanism that explains the

localized production of hot H over the larger plasma chamber is required. Mills' hypothesis of a

catalytic reaction of hydrogen is consistent with the observation of hot H atoms far way from the

high field region.

In order to explain the symmetric line emission profile, the CM model mandates the

presence of a reflector or divertor. In this model a Gaussian distribution is achieved either by the

scattering of hydrogen atoms by the electrode surface or by collisional excitation of H$_f$ on H$_2$

with large angle scattering [6], where H_f represents the hot hydrogen atoms that have previously collided with the electrode. This implies that the sputtered fast H atoms and the back-reflected fast H atoms from the cathode surface are produced in equal measure to produce a symmetric profile. This requires an "ideal isotropic reflector" to reverse the momentum of a positive ion gained from the electric field to give rise to fast H leaving the cathode in the same abundance as that moving towards the cathode. In addition, according to their model, a "divertor" must also exist such that the ratio of fast H at any given energy towards and away from the cathode remains equal and this must be the case in all directions including the direction perpendicular to the electric field. The interaction of an H atom with a metal surface is quasi-elastic for a large range of targets and energies. The particle and energy reflection coefficients for hydrogen atoms to be reflected back in the energy range of 20-30 eV are only 50% [40]. Therefore, the possibility that backscattered H atoms produced with a comparable distribution to those of the incident H atoms with comparable energy distributions so as to yield a symmetric profile is not feasible. In addition, it is well known that the effective cross section for many small-angle ion-neutral collisions to produce an equivalent deflection is larger than that for single large-angle collision [41]. Hence, this argument is not viable as a mechanism to explain the symmetry of the plasma emission profile.

Electron-ion, electron-neutral, and ion-neutral collision frequencies are a complex function of not only the gas pressure but also of the energy of the colliding particles. Therefore, in order to obtain a better insight into the energy transfer through the collision and charge exchange process, an estimate of the collision frequencies at the pressure and energies of interest is discussed. For a flux of incident electrons with velocities v colliding with a background neutral gas, the collision frequency is given approximately as $v_{cn} = n_g \sigma v = n_g K \sim 3 \times 10^9 \times P(Torr)s^{-1}$

22

where n_g is the neutral number density given by Loschmidt's number and σ is the collision cross-section and K is the rate constant [41-42]. At 10 mTorr and 10 Torr, the electron-neutral collision frequencies are 3×10^7 s^{-1} and 3×10^{10} s^{-1}, respectively, a variation of three orders of magnitude. Therefore at 10 mTorr, the electron-neutral collision frequency is comparable to the rf frequency and the electron can travel to the anode in one rf period of 73 ns. The LP measured electron temperature is 2-3 eV and the electron can travel a distance of about 8 cm during one rf period without suffering collisions with the background neutral gas. Therefore, in low-collision-rate plasmas compared to the ion transit time between the electrodes, based on the CM, fast H atoms produced by the charge exchange process will continue to move towards the direction of the accelerated ions and will yield a predominant red or blue wing in the emission spectrum relative to the direction of observation. However, the data presented in this paper are contrary to the prediction of the CM field acceleration mechanism of energy transfer to hydrogen atom. The symmetric line profile is independent of the angle of observation.

VI   CONCLUSION

The mechanism of extraordinary broadening of the hydrogen Balmer lines in hydrogen admixed with noble gases has been studied in two different discharge systems over a wide parameter range to examine highly collisional and weakly collsional regimes. Experiments were performed to test the validity of the field acceleration based Collisional Model. The field acceleration based Collisional Models were formulated to explain the energy gained by hydrogen atoms in experiments where only hydrogen plasmas and plasmas of hydrogen admixed with much heavier noble gases (Ar) were considered. As a result, the selective transfer of energy only to the hydrogen atom was not considered while theories were formulated to explain the

23

extraordinary broadening. However, we have found that energy is transferred only to hydrogen atoms and not to the admixed gases even when the admixed gas is helium with a mass ratio of 4:1. It was also realized that this energy transfer is not the same even when the admixed gases are electronically similar. For example, hot H atoms are absent when He and Ar are replaced with an electronically similar noble gas Xe. The directionality of energy gained according to the field acceleration based CM mechanism was tested by using sharp tipped electrodes in a DC discharge, thus minimizing the electrode surface area perpendicular to the axis. The plasma emission parallel and perpendicular to the electric field lines was sampled over a wide pressure range. The H_α line profiles were observed to be symmetric in all cases. As discussed earlier, this symmetry can not be explained by the field acceleration based CM model, including its variations where it is argued that equally hot H atoms in equal measure are produced by backscattering with the cathode surface.

Moreover, the Collisional Model utilizes the presence of a plasma sheath where most of the ions are accelerated and these then transfer energy to hydrogen atoms through the charge exchange process. It has been shown in this paper that hot hydrogen atoms are observed far away from the cathode fall regions in plasmas. The presence of hot H in a region where the plasma potential variation is low and plasma electrons are cold ($T_e < 2$ eV), is clearly in contrast to the CM. It is concluded that these observations are consistent with the RT-plasma mechanism.

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TABLE 1

Langmuir probe measurement of plasma density and electron temperature in capacitively coupled radio frequency plasmas at 100 mTorr and 100 W coupled rf power.

Gas Composition	Bulk Plasma Density (cm^{-3})	Bulk Electron Temperature (eV)
Ar	$2\text{-}3 \times 10^{10}$	2.1-2.4
Ar/10%H_2	$5\text{-}8 \times 10^9$	1.8-2.0
He	$6\text{-}9 \times 10^9$	2.5-3.0
He/10%H_2	$3\text{-}5 \times 10^9$	1.9-2.3
Xe	$2\text{-}5 \times 10^{10}$	1.7-2.0
Xe/10%H_2	$7\text{-}9 \times 10^9$	1.7-1.9

30
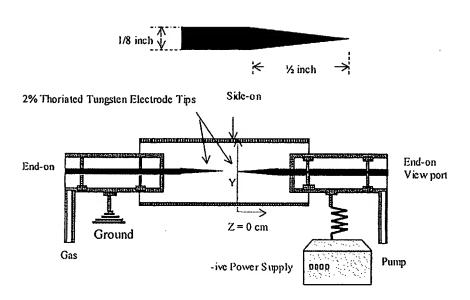
Fig 1. Schematic of the DC discharge created between the fine tips of 2% thoriated tungsten electrodes with the direction of axial scans defined. The cathode tip is taken as z=0 cm for side-on observations measured along the axis of the cathode from its tip to its electrical connection.
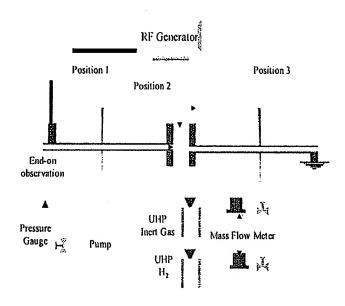
Fig.2: Schematic of the capacitively coupled radio frequency plasma system. Optical emission spectroscopy is performed perpendicular to the electric field (Position 2) and parallel to the field (end-on observation).
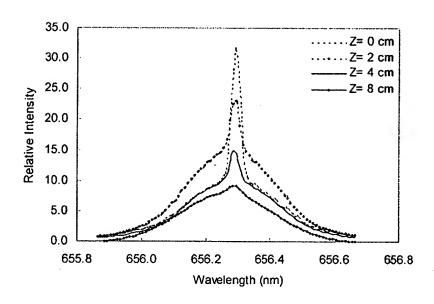
Fig. 3. Axial scan of the 656.3 nm Balmer α line width recorded on a 1 Torr Ar /H₂ (95/5%) DC plasma discharge with needle-like electrodes at 400 V and 20 mA showing 80% of the hydrogen was 'hot' with an average hydrogen atom energy of 40 eV, compared to < 0.5 eV for the slow population.
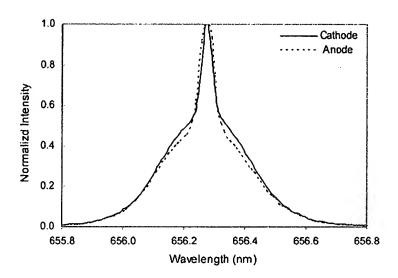
Fig. 4. The 656.3 nm Balmer α line width recorded end-on (parallel to the electric field) on a 1 Torr *Ar* /H₂ (95/5%) DC plasma discharge with needle-like electrodes at 400 V and 20 mA. Both views looking towards the cathode as well as the anode show a symmetrical emission profile. The temperature of hot hydrogen atoms is in the range of 38-40 eV.
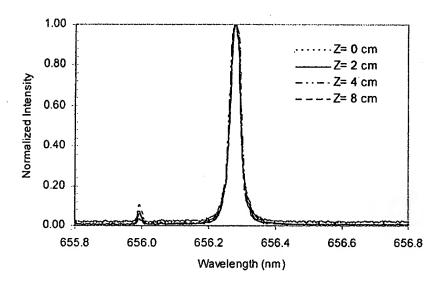
Fig. 5. Axial scan of the 656.3 nm Balmer α line width recorded on a 1 Torr *Xe* /H₂ (95/5%) DC plasma discharge with needle-like electrodes at 400 V and 20 mA showing only a cold population of <1 eV with a decrease in intensity along the cathode due to a decrease in electron density and energy.
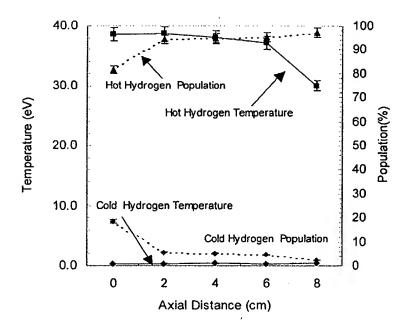
Fig. 6. Axial plots of hot hydrogen atoms temperature and population (given by area under the curve) corresponding to the spectrum in Figure. 3. A hot hydrogen population is present even at a distance of 8 cm away from the cathode tip where most of the potential falls.
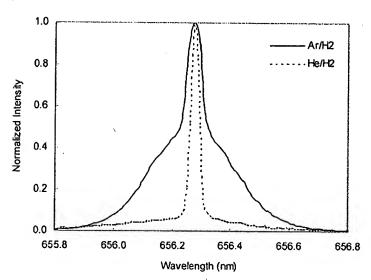
36

Fig. 7 Normalized end-on emission spectrum of 1 Torr Ar/5%H₂ and He/5%H₂ plasma looking towards the anode. Note the symmetrical emission profile.
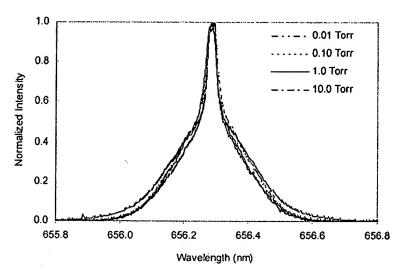
Fig. 8 Normalized end-on emission spectrum of Ar/5%H$_2$ plasma looking towards cathode as the gas pressure is varied over three-orders-of magnitude from 10 mTorr to 10 Torr. Note the symmetrical emission profile.
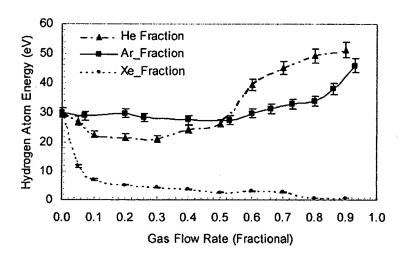
Fig.9 Energy of hot hydrogen atoms as a function of fractional concentration of admixed gases in a DC discharge at 100 mTorr. Note the increase in the energy of hot H as Ar and He concentration increases and decrease in energy with the addition of Xe.
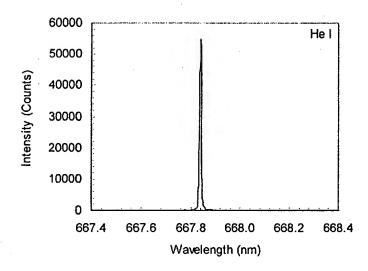
Fig. 10

Fig. 10 The 667.816 *nm* He I line width for 1 Torr He/H₂ (95/5%) at 400 V and 20 mA . No broadening was observed,
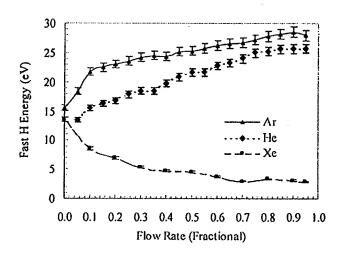
Fig.11. Energy of hot hydrogen atom in Ar/H$_2$, He/H$_2$ and Xe/H$_2$ plasmas as a function of the noble gas concentration [H$_2$(x) Ar, He, Xe(y=1-x)] in capacitively coupled rf discharge. The plasma chamber is maintained at 150 mTorr with a total flow rate of 20 sccm. The coupled rf power is 200 Watt. H$_\alpha$ emission is sampled perpendicular to the electric field between the capacitive plates.
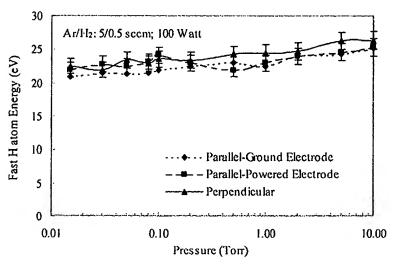
Fig. 12: Hot hydrogen atom temperature for capacitively coupled Ar/H₂ discharge at different gas pressures. Observations are made perpendicular to the field between the electrodes and parallel to the field lines through holes in both powered and grounded electrodes.
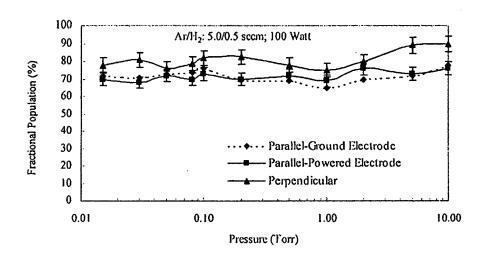
Fig.13. Fractional population of hot hydrogen atoms in n=3 excited state in a capacitively coupled Ar/H₂ discharge at different gas pressures.
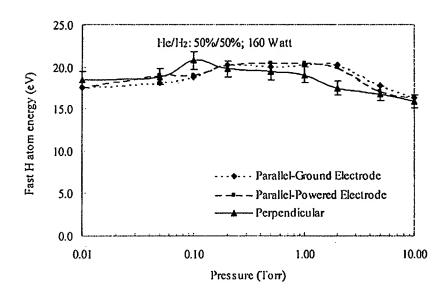
Fig.14. Hot hydrogen atom energy in a capacitively coupled He/H$_2$ discharge at different gas pressures.
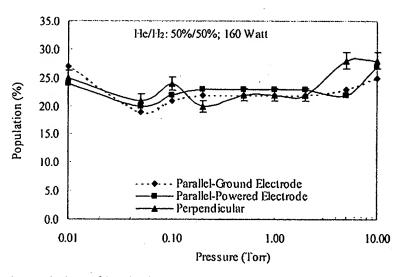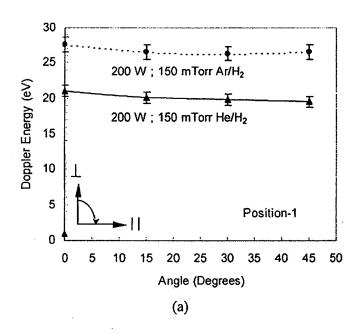
Fig.15. Fractional population of hot hydrogen atoms (n=3 state) in a capacitively coupled He/H₂ discharge at different gas pressures.
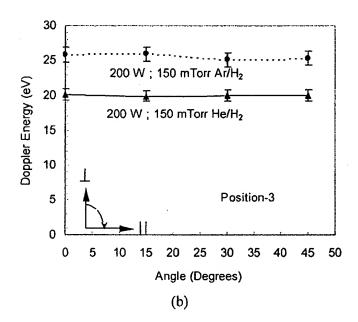
Fig.16. Angular variation of Doppler energy of hot hydrogen atom in a capacitively coupled radio frequency discharge at 150 mTorr 50%Ar/50%H₂ and 50%He/50%H₂ plasma at 200 W. Plasma emission is sampled at Position 1 (Fig. a) and Position 3 (Fig. b) far away from the region of high field in plasma sheath. Reference is normal to the chamber axis.

Water Bath Calorimetry on a Catalytic Reaction of Atomic Hydrogen

R. L. Mills*, H. Zea, J. He, B. Dhandapani

BlackLight Power, Inc.

493 Old Trenton Road

Cranbury, NJ 08512

ABSTRACT

Plasmas of certain catalysts such as Sr^+ and Ar^+ mixed with hydrogen were studied for evidence of a novel energetic reaction. These hydrogen plasmas called resonant transfer- or rt-plasmas were observed to form at low temperatures (e.g. $\approx 10^3 \ K$) and extraordinary low field strengths of about 1-2 V/cm when argon and strontium were present with atomic hydrogen. Time-dependent line broadening of the H Balmer α line was observed corresponding to extraordinarily fast H (25 eV). When an argon-hydrogen hollow-anode glow discharge plasma with strontium metal contained in the cell was optimized for Sr^+ emission, an average hydrogen hot atom temperature of $50.2 \ eV$ with a 83.5% population and an excess power of 28.5% of the input power were observed. Using water bath calorimetry, an excess power of 2.85 W was measured on rt-plasmas with Sr^+ and Ar^+ as catalysts and atomic hydrogen as a reactant, compared with controls with no hydrogen and no catalyst present. The energy balance was high. Given an argon-hydrogen (95/5 %) flow rate of 1.0 sccm and an average excess power of 2.85 W and energy balances of over $-7.7 \ X \ 10^4 \ kJ / mole \ H_2$ were measured.

Keywords: catalysis, rt-plasma, fast H, excess power

* To whom correspondence should be addressed. Phone: 609-490-1090; Fax: 609-490-1066; E-mail: rmills@blacklightpower.com

1. Introduction

A new chemically generated or assisted plasma source has been developed that is based on a resonant energy transfer mechanism (rt-plasma). One such source operates by incandescently heating a hydrogen dissociator and a catalyst to provide atomic hydrogen and gaseous catalyst, respectively, such that the catalyst reacts with the atomic hydrogen to produce a plasma. It was extraordinary that intense EUV emission was observed by Mills, et al. [1-4] at low temperatures (e.g. $\approx 10^3\ K$) and an extraordinary low field strength of about 1-2 V/cm from atomic hydrogen and certain atomized elements or certain gaseous ions, which singly or multiply ionize at integer multiples of the potential energy of atomic hydrogen, 27.2 eV. A number of independent experimental observations [1-26] confirm that the rt-plasma is due to a novel reaction of atomic hydrogen which produces as chemical intermediates, hydrogen atoms in fractional quantum states that are at lower energies than the traditional "ground" ($n = 1$) state. Power is released, and the final reaction products are novel hydride compounds. The supporting data include EUV spectroscopy [1-7, 10, 14-20, 23], characteristic emission from catalysts and the hydride ion products [1-4, 14, 16-20], lower-energy hydrogen emission [5-7, 23], chemically formed plasmas [1-4, 14-20], Balmer α line broadening [1-6, 8-14, 16, 19-20, 23], population inversion of H lines [19-21], elevated electron temperature [6, 8-9], anomalous plasma afterglow duration [14-15], power generation [6, 10, 14, 22-23], and analysis of novel chemical compounds [14, 24-26].

The theory given previously [27-29] is based on applying Maxwell's equations to the wave equation. The familiar Rydberg equation (Eq. (1)) arises for the hydrogen excited states for $n > 1$ of Eq. (2).

$$E_n = -\frac{e^2}{n^2 8\pi\varepsilon_o a_H} = -\frac{13.598\ eV}{n^2} \tag{1}$$

$$n = 1, 2, 3, \dots \tag{2}$$

An additional result is that atomic hydrogen may undergo a catalytic reaction with certain atoms and ions, which singly or multiply ionize at integer multiples of the potential energy of atomic hydrogen, $m \cdot 27.2\ eV$, wherein m is an integer. The reaction involves a nonradiative energy transfer to form a hydrogen atom that is lower in energy than unreacted atomic hydrogen that corresponds to a fractional principal quantum number. That is

$$n = \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots, \frac{1}{p}; \quad p \text{ is an integer} \tag{3}$$

replaces the well known parameter $n =$ integer in the Rydberg equation for hydrogen excited states. The $n = 1$ state of hydrogen and the $n = \dfrac{1}{\text{integer}}$ states of hydrogen are nonradiative, but a transition between two nonradiative states, say $n = 1$ to $n = 1/2$, is possible via a

nonradiative energy transfer. Thus, a catalyst provides a net positive enthalpy of reaction of $m \cdot 27.2 \, eV$ (i.e. it resonantly accepts the nonradiative energy transfer from hydrogen atoms and releases the energy to the surroundings to affect electronic transitions to fractional quantum energy levels). As a consequence of the nonradiative energy transfer, the hydrogen atom becomes unstable and emits further energy as $q \cdot 13.6 \, eV$ emission [5-7] or $q \cdot 13.6 \, eV$ transfer to H to form extraordinarily hot, excited-state H [8-13] until it achieves a lower-energy nonradiative state having a principal energy level given by Eqs. (1) and (3). Processes such as hydrogen molecular bond formation that occur without photons and that require collisions are common [30]. Also, some commercial phosphors are based on resonant nonradiative energy transfer involving multipole coupling [31].

Certain atoms, excimers, and ions which provide a reaction with a net enthalpy of an integer multiple of the potential energy of atomic hydrogen, $E_h = 27.2 \, eV$ where E_h is one hartree. Specific species (e.g. He^+, Ar^+, K, and Sr^+) identifiable on the basis of their known electron energy levels are required to be present in plasmas with atomic hydrogen to catalyze the process. In contrast, species such as atoms or ions of Mg or Xe do not fulfill the catalyst criterion—a chemical or physical process with an enthalpy change equal to an integer multiple of E_h that is sufficiently reactive with atomic hydrogen under reaction conditions.

Ar^+ may serve as a catalyst since its ionization energy is about $27.2 \, eV$. Also, since the ionization energy of Sr^+ to Sr^{3+} has a net enthalpy of reaction of $2 \cdot 27.2 \, eV$, Sr^+ may serve as catalyst alone or with Ar^+ catalyst. It was reported previously that an rt-plasma formed with a low field (1V/cm), at low temperatures (e.g. $\approx 10^3 \, K$), from atomic hydrogen generated at a tungsten filament and strontium which was vaporized by heating the metal [1-4]. Strong VUV emission was observed that increased with the addition of argon, but not when sodium, magnesium, or barium replaced strontium or with hydrogen, argon, or strontium alone. Characteristic emission was observed from a continuum state of Ar^{2+} at $45.6 \, nm$ without the typical Rydberg series of Ar I and Ar II lines which confirmed the resonant nonradiative energy transfer of $27.2 \, eV$ from atomic hydrogen to Ar^+ [2, 4, 18]. Predicted Sr^{3+} emission lines were also observed from strontium-hydrogen plasmas [2, 4] that supported the rt-plasma mechanism.

Significant Balmer α line broadening corresponding to an average hydrogen atom temperature of 14 eV and 24 eV was observed for strontium and argon-strontium rt-plasmas and 23-45 eV for discharges of strontium-hydrogen, helium-hydrogen, argon-hydrogen, strontium-helium-hydrogen, and strontium-argon-hydrogen, compared to $\approx 3 \, eV$ for pure hydrogen, krypton-hydrogen, xenon-hydrogen, and magnesium-hydrogen. To achieve that same optically measured light output power, sodium-hydrogen, magnesium-hydrogen, and barium-hydrogen mixtures required 4000, 7000, and 6500 times the power of the strontium-

hydrogen mixture, respectively, and the addition of argon increased these ratios by a factor of about two. A glow discharge plasma formed for strontium-hydrogen mixtures at an extremely low voltage of about 2 V compared to 250 V for hydrogen alone and sodium-hydrogen mixtures, and 140-150 V for magnesium-hydrogen and barium-hydrogen mixtures [1-2, 4]. These voltages are too low to be explicable by conventional mechanisms involving accelerated ions with a high applied field.

To further characterize argon-strontium rt-plasmas, plasma formation was studied relative to mixtures of hydrogen and a chemically similar control that does not have electron ionization energies which are a multiple of 27.2 eV, and the Balmer lines were recorded by visible spectroscopy to confirm that an energetic hydrogen plasma was present having H energy states greater than 12 eV corresponding to $n \geq 3$ in Eqs. (1-2). The broadening of the Balmer α line was also recorded as a function of time, and thermal power balance measurements were performed. The cell comprised a titanium or tungsten filament to heat and vaporize some strontium as a source of catalyst and to dissociate molecular hydrogen to atomic hydrogen. The addition of argon to the plasma further provided the catalyst Ar^{+}.

Since a conventional discharge power source was not present, the formation of a plasma would require an energetic reaction. The origin of Doppler broadening is the relative thermal motion of the emitter with respect to the observer—in this case the spectrometer. Line broadening is a measure of the atom temperature, and a significant increase was expected and observed for catalysts from strontium or argon with hydrogen. The observation of a high hydrogen temperature with no conventional explanation would indicate that an rt-plasma must have a source of free energy. An energetic chemical reaction was further indicated since it was found that the broadening is time dependent. Therefore, the thermal power balance was measured calorimetrically. To maintain a constant level of ionized argon and strontium as catalysts, a DC glow discharge of plasma of argon-hydrogen (97/3%)-strontium was maintained using a hollow anode. The energy balance was measured by water bath calorimetry. We report the results of these characterizations and discuss the implications regarding the rt-plasma mechanism in Secs. 3A-C.

2. Experimental

Balmer Line Broadening. An argon-hydrogen (97/3%)-strontium rt-plasma was generated in the experimental set up (Figure 1) described previously [1-4] comprising a thermally insulated quartz cell with a cap that incorporated ports for gas inlet, and outlet. A titanium filament (55 cm long, 0.5 mm diameter) that served as a heater and hydrogen dissociator was in the quartz tube. 2.5 g of magnesium or strontium metal (Alfa Aesar 99.95%) was placed in the center of the cell under one atmosphere of dry argon in a glovebox.

4

The cell was sealed and removed from the glovebox. The cell was maintained at 50 °C for four hours with helium flowing at 30 sccm at a pressure of 0.6 Torr. The filament power was increased to 120 W in 20 increments every 20 minutes. At 120 W, the filament temperature was estimated to be in the range 800 to 1000 °C. The external cell wall temperature was about 700 °C. The cell was then operated with and without an argon-hydrogen (90/10%) flow rate of 5.5 sccm maintained at 0.6 Torr. Additionally, the cell was operated with hydrogen and argon-hydrogen (90/10%) gas flow and no metal. Each metal was vaporized by the filament heater. The presence of a hydrogen plasma was determined by recording the visible spectrum over the Balmer region with a Jobin Yvon Horiba 1250 M spectrometer with a PMT detector described previously [8-9] using entrance/exits slits of 200/100 μm, 0.1 Å step size, and a 3 s integration time. The width of the 656.3 nm Balmer α line emitted from the argon-hydrogen (90/10%)-strontium rt-plasma having a titanium filament was measured initially and periodically during operation. The Balmer profile was also recorded on the air-gap, glow discharge reactor described in the next section with an input power of 20 W (V=200; I=0.1A).

Power balance measurements. The power balance of a rt-plasma of strontium with argon-hydrogen mixture (95/5%) maintained in an air-gap, glow discharge reactor shown in Figure 2 was measured by water bath calorimetry using the experimental setup shown in Figure 3. Excess power was observed from argon-hydrogen-strontium plasmas compared to calibration control experiments with the same input power.

The reaction cell comprised a cylindrical stainless steel case of 5.1 cm OD and 17.2 cm in length welded to a set of high vacuum, 8.6 cm diameter Con-flat flanges, as shown in Figure 2. A silver plated copper gasket was placed between a mating flange and the cell flange. The two flanges were clamped together with 10 circumferential bolts. The top-mating flange had a radial centered stainless steel hollow feed through that extended 8.6 cm into the cell and was partially covered by a 3.6 cm long ceramic sleeve, measured from the flange. Gas was fed into the cell by a 1 cm OD stainless steel tube welded to the top-mating flange. Gas flow was controlled by a 0-20 sccm range mass flow controller (MKS model M100B21CS1BV). The cell pressure was monitored by a 0-10 Torr MKS Baratron (model 626A11TEE) absolute pressure gauge. Additionally, the top-mating flange had a drilled thermo well that housed a stainless steel thermocouple (0.3 cm OD). Two 1 cm OD stainless steel tubes were welded to the bottom wall of the reaction cell. One carried the exhaust gas, and the other served as a connection port for a 0.6 cm OD and 16.5 cm long quartz rod to perform optical emission spectroscopy studies. In an oxygen free environment (glove box), 4 grams of strontium distributed in 15 pieces was loaded into the reaction cell and placed below the hollow electrode

5

as shown in Figure 2, the reaction cell was transferred into the stainless steel jacket, and all the gas and electrical connections were fitted and checked for leaks.

The reaction cell was housed inside a cylindrical stainless steel jacket of 15.2 cm OD and 30.5 cm in length with a removable front flange having welded Ultratorr connectors that fit the reaction cell gas line and the thermocouple. The bottom wall of the stainless steel jacket had two welded Ultratorr connections that fitted the reaction cell exhaust gas and the quartz rod connection port. Two 0.41 cm OD copper power feed-throughs were welded on the side wall and that provided electrical connectors for the reaction cell when it was placed inside the stainless steel jacket. The jacket housing containing the reaction cell was placed inside the drained water bath container, the gas inlet and outlet tubes were connected to the gas/vacuum manifold, as shown in Figure 3.

The water bath (Figure 3) comprised an insulated reservoir filled with 41 liters of de-ionized water. The water was agitated with a paddle driven by a stirring motor. A high precision linear response thermistor probe (Omega OL-703) recorded the temperature of the water bath as a function of time for the stirrer alone to establish the baseline. The water bath was calibrated by a high precision heater (Watlow LGEX17B Type CR-1, with a Xantrex XDC power supply 0-6000 $\pm$ 0.01 W). Each experiment comprised three distinctive periods: pre-period, heating period, and post period. The pre-period was performed with no power applied to the electrode or to the heater during the reaction test or calibration test, respectively. During the heating period, power was applied through the electrode or through the heater. In the post period, the power applied during the heating period was turned off. The water of the bath was agitated with a stirrer spinning at constant speed throughout all three periods.

The heat capacity was determined for several input powers, 10, 20, 30, 40, and 50 W $\pm$ 0.01 W, and was found to be independent of input power over this power range within $\pm$ 1.8 %. The temperature rise of the reservoir as a function of time gave a slope in °C/s. This slope was baseline corrected for the stirrer power and loss to ambient. The constant known input power (J/s), was divided by this slope to give the heat capacity in J/°C. Then, in general, the total power output from the cell to the reservoir was determined by multiplying the heat capacity by the rate of temperature rise (°C/s) to give J/s.

The power balance for a plasma system consisting of the contents of the water bath calorimeter is [23]

6

$$\dot{H} = \dot{M}\left(\hat{H}_{in} - \hat{H}_{out}\right) + \dot{Q}_{plasma} + \dot{Q}_{power\ cable} + \dot{Q}_{stirrer} + \dot{Q}_{heat\ exchange} \qquad (4)$$

where H's are enthalpy values (inlet and outlet gases as indicated by the subscripts in and out, respectively, and the hat designates per mole), $\dot{M}$ is the molar flow rate, and the $\dot{Q}$'s are heat flow rates. It is clear from Eq. (4) that a correction must be considered both for the gas flow term (first term, right side), '$\dot{Q}_{power\ cable}$' which represents the input of the section (approx. 80 cm long) of the power cable that passes through the water bath as it brings power to the discharge, for the work of the stirrer, and for the heat exchange between the insulated water bath and its surroundings.

The values of '$\dot{Q}_{power\ cable}$' and the heat carried out with the gas were small, as determined by appropriate temperature readings. Thermocouples were employed to measure the temperature of the input and output gas, as well as the temperature of the power cable just outside the water bath. Given that the temperature of the power cable was the same as the water bath, $\dot{Q}_{power\ cable}$ was taken as zero. The gas temperature change between input to the plasma and output from the water bath was never more than 1 K. Heat transfer from cell containing the flowing gas to the water in the bath was clearly very efficient. Given the flow rate was 1 sccm, this requires a maximum correction of less than 10^{-6} W, a trivial correction. The stirrer and heat exchange terms were found to be the most significant correction, but its value was readily determined by measuring the temperature rise with only the stirrer operating. This correction can be accurately calculated from the slope of the pre- and post-heating periods and was found to be constant, 5.0 W for all experiments. Once these relatively trivial corrections are made, the 'effective' energy balance becomes:

$$\dot{H} = \dot{Q}_{plasma} \qquad (5)$$

The calibration procedure resulted in a linear change in temperature for constant power inputs. This is expected, given the nearly constant heat capacity of water over small changes in temperature (<14 K in all cases). Thus, changes in enthalpy can be readily equated with change in temperature of the bath. In short:

$$\dot{H} = C_p \dot{T} = \dot{Q}_{plasma} \qquad (6)$$

Thus, one must only multiply the calibration constant by the rate of change of bath temperature to obtain the plasma's heating power of the water bath. In the event that the change in temperature is nearly linear with time, as it was in all cases in this study, the rate (W) of heat input from the plasma to the bath can be readily determined, and compared with the input power. The rt-plasma results were compared with the results of the calibration control experiment determined using the same analytical procedure .

Since the cell and water bath system were adiabatic, the general form of the power balance equation with the possibility of excess power is:

7.

$$P_{in} + P_{ex} - P_{out} = 0 \qquad (7)$$

where P_{in} is the input discharge or heater power, P_{ex} is the excess power generated from the hydrogen catalysis reaction, and P_{out} is the thermal power loss from the cell to the water bath.

The plasma voltage and current reached steady state in about 5 to 10 minutes after the heating period started, and the temperature measured at the wall of the cell typically reached a steady state in about 1 to 2 hrs after the heating period was started. At this point, the power lost from the cell P_{out} was equal to the power supplied to the cell, P_{in}, plus any excess power P_{ex}.

$$P_{in} + P_{ex} = P_{out} \qquad (8)$$

Since the cell was surrounded by water that was contained in an insulated reservoir with negligible thermal losses as discussed above, the temperature response of the thermistor T as a function of time t was modeled by a linear curve

$$\dot{T}(t) = a^{-1} P_{out} \qquad (9)$$

where a is the heat capacity (J/°C) for the least square curve fit of the response to power input for the control experiments ($P_{ex} = 0$). The slope was recorded for about 25 hours after the cell was started, to achieve an accuracy of $\pm$ 1.8%.

The slope of the temperature rise as a function of time was recorded for each run and baseline corrected for the stirrer power and loss to ambient, then the output power was calculated from the corrected slope. After the calorimeter was calibrated, $T(t)$ was recorded with a selected power to the plasma and compared to the results of identical input to the heater in a separate run of the identical system. The higher slope produced with argon-hydrogen-strontium plasma, having Sr^+ and Ar^+ as catalysts and atomic hydrogen as a reactant, compared with controls with no hydrogen and no catalyst present was representative of the excess power. In the case of the catalysis run, the total output power P_{out} was determined by solving Eq. (9) using the measured $\dot{T}(t)$ and the heat capacity a. The excess power P_{ex} was determined from Eq. (8).

3. Results and discussion

A. RT-plasma emission

An argon-hydrogen (90/10%)-strontium rt-plasma formed with a low field (1V/cm), at low temperatures (e.g. $\approx 10^3$ K), from atomic hydrogen generated at a titanium filament and strontium which was vaporized by heating the metal. H Balmer emission corresponding to population of a level with energy > 12 eV was observed as shown in Figure 4 which also requires that Lyman emission was present. No plasmas formed when magnesium replaced strontium or with hydrogen, argon/hydrogen, or strontium alone. This result indicates that the

emission was due to a reaction of hydrogen with vaporized strontium. No possible chemical reactions of the titanium filament, the vaporized strontium, and 0.6 Torr argon-hydrogen mixture at a cell temperature of 700°C could be found, which accounted for the Balmer emission. In fact, no known chemical reaction releases enough energy to excite Balmer and Lyman emission from hydrogen. In addition to known chemical reactions, electron collisional excitation, resonant photon transfer, and the lowering of the ionization and excitation energies by the state of "non ideality" in dense plasmas were also rejected as the source of ionization or excitation to form the hydrogen plasma [15]. The formation of an energetic reaction of atomic hydrogen was consistent with a source of free energy from the catalysis of atomic hydrogen by Sr^+ and Ar^+.

B. Balmer α line widths

The energetic hydrogen atom energies were calculated from the Doppler width of the 656.3 nm Balmer α line emitted from RF rt-plasmas [8-9]. The full half-width $\Delta \lambda_G$ of each Gaussian results from the Doppler ($\Delta \lambda_D$) and instrumental ($\Delta \lambda_I$) half-widths:

$$\Delta \lambda_G = \sqrt{\Delta \lambda_D^2 + \Delta \lambda_I^2} \qquad (10)$$

$\Delta \lambda_I$ in our experiments was $0.006 \, nm$. The temperature was calculated from the Doppler half-width using the formula:

$$\Delta \lambda_D = 7.16 \, X \, 10^{-7} \lambda_0 \left(\frac{T}{\mu} \right)^{1/2} \qquad (11)$$

where λ_0 is the line wavelength, T is the temperature in K ($1 \, eV = 11,605 \, K$), and μ is the molecular weight (=1 for atomic hydrogen). In each case, the average Doppler half-width that was not appreciably changed with pressure varied by $\pm5\%$ corresponding to an error in the energy of $\pm10\%$.

The 656.3 nm Balmer α line widths recorded on the argon-hydrogen (90/10%)-strontium rt-plasma having a titanium filament initially and after 70 hours of operation are shown in Figure 4. Significant broadening was not observed initially. However, the Balmer α line profile of the plasma emission after 70 hours comprised two distinct Gaussian peaks, an inner, narrower peak corresponding to a slow component with an average hydrogen energy of 1 eV and an outer broader peak corresponding to a fast component of 20 eV. Only the hydrogen lines were broadened. These results are consistent with the catalysis of hydrogen to lower-states followed by subsequent transitions with increasing energy release by an autocatalytic mechanism previously reported with spectroscopic evidence [7-8].

We have assumed that Doppler broadening due to thermal motion was the dominant source to the extent that other sources may be neglected. This assumption was confirmed

when each source was considered. In general, the experimental profile is a convolution of two Doppler profiles, an instrumental profile, the natural (lifetime) profile, Stark profiles, van der Waals profiles, a resonance profile, and fine structure. The contribution from each source was determined to be below the limit of detection [1-6, 8-14, 16, 19-20, 23].

The emission spectrum from the hollow anode, glow discharge of argon-hydrogen (95/5%)-strontium (Figure 5a) showed an intense Sr^+ (407.77 nm) line. The selectively Doppler-broadened 656.3 nm Balmer α line width recorded with a high resolution visible spectrometer corresponding to an average hydrogen hot atom temperature of $50.2\ eV$ with a 83.5% population is shown in Figures 5b and 5c. The independence of the broadening and the peak shape with position in the cell or the dependence on applied voltage or pressure over a broad range excludes the only conventional explanation of a field acceleration mechanism as discussed previously [1-6, 8-14, 16, 19-20, 23].

The formation of fast H can be explained by a resonant energy transfer from hydrogen atoms to Sr^+ or Ar^+ ions of two and one times the potential energy of atomic hydrogen, respectively, followed by a collisional energy transfer to yield fast $H(n=1)$, as well as the emission of $q \cdot 13.6\ eV$ photons reported previously [5-7]. For example, the exothermic chemical reaction of $H + H$ to form H_2 does not occur with the emission of a photon. Rather, the reaction requires a collision with a third body, M, to remove the bond energy- $H + H + M \rightarrow H_2 + M^*$ [30]. The third body distributes the energy from the exothermic reaction, and the end result is the H_2 molecule and an increase in the temperature of the system. In the case of the catalytic reaction with the formation of states given by Eqs. (1) and (3), the temperature of H becomes very high.

C. Power balance of the rt-plasma cell

The thermogram, $T(t)$ response of the air-gap reactor with an input power of 10 W to maintain an argon-hydrogen (95/5%)-Sr^+ plasma compared to the heater calibration with stirring only and with a constant input power to the high precision heater of 10 W is shown in Figure 6a. It is evident that the value of the heating slope of the calibration experiment (heater) is smaller than the value of the reaction test, implying that for the same experimental conditions and input power, the rt- plasma transferred more heat to the water than the control performed using the high precision heater. According to Eq. (6), the water bath temperature is a direct indication of the amount of heat generated inside the reaction cell and transferred to the system; therefore, the results of this study show that the argon-hydrogen (95/5%)-strontium plasma generated heat in excess of the input power.

10

The average baseline corrected least squares fit of the slope, $\dot{T}(t)$, for several calibrations was $5.23 \, X \, 10^{-5} \, °C/s$, and the heat capacity determined from Eqs. (8-9) with $P_{ex} = 0$, and $P_{in} = P_{out} = 10 \, W$ was $1.911 \, X \, 10^5 \, J/°C$. Then the temperature response of the calorimeter for any case (Eq. (9)) was determined to be

$$\dot{T}(t) = \left(1.911 \, X \, 10^5 \, J/°C\right)^{-1} \times P_{out} \tag{12}$$

Also a plot of the evolution of excess heat as a function of time can be obtained by using the same heat capacity multiplied by the delta temperature between the reaction and calibration test profiles and further dividing by the time increment:

$$P_{ex}^i = \frac{C_p(T_r^i - T_c^i)}{t_i - t_0} \tag{13}$$

where P_{ex}^i is the excess heat, T_r^i and T_c^i are the water bath temperature of the reaction test and the calibration test at time t_i, respectively, and t_0 is the time at which the heating period started. The excess power obtained for the plasma reaction as a function of time determined by using the measured $\dot{T}(t)$, the input power of 10.0 W, and Eqs. (8) and (9), is shown in Figure 6b. The typical excess heat observed was 2.85 W. These results agree with those obtained using Eq. (13). Sources of error were the error in the calibration curve ($\pm$ 0.05 W) and the measured input power ($\pm$ 0.01 W). The propagated error of the calibration and power measurements was $\pm$ 0. 05 W.

Given an argon-hydrogen (95/5%) flow rate of 1.0 sccm and an average excess power of 2.85 W, energy balances of over $-7.7 \, X \, 10^4 \, kJ/mole \, H_2$ ($471 \, eV/H \, atom$) were measured. The reaction of hydrogen to form water, which releases $-241.8 \, kJ/mole \, H_2$ ($1.48 \, eV/H \, atom$) is about 320 times less than that observed. The results indicate that once an atom given by Eqs. (1) and (3) is formed by a catalyst, further catalytic transitions $n = \frac{1}{3} \to \frac{1}{4}, \, \frac{1}{4} \to \frac{1}{5}$, and so on, occur to a substantial extent. This is consistent with the series of lower-energy hydrogen lines with energies of $q \cdot 13.6 \, eV$ where $q = 1, 2, 3, 4, 6, 7, 8, 9, \, or \, 11$ [5-7], the previously given theory [1-7, 27-29], and previous studies which show very large energy balances [6, 10, 14, 22-23]. These results were confirmed by Calvet and water-flow calorimetry.

4. Conclusion

An rt-plasma formed with a low field (1V/cm), at low temperatures (e.g. $\approx 10^3\,K$), from argon and atomic hydrogen generated at a titanium filament with strontium which was vaporized by heating the metal. Strong Balmer emission was observed that indicated an energy source of $> 12\,eV$. The energetic reaction of atomic hydrogen was anticipated to form energetic hydrogen atoms. Significant Balmer α line broadening corresponding to an average hydrogen atom temperature of 20 eV was observed. The time-dependence of the appearance of fast H supported an energetic chemical reaction as the source. The power balance of a rt-plasma with Sr^+ and Ar^+ as catalysts was measured by water bath calorimetry. An average excess power of 2.85 W was observed. The enthalpy of formation ΔH_p of strontium hydride is $-199.1\,kJ/mole$ ($1.0\,eV/H\,atom$) [32]. Thus, the energy for hydriding all of the 4 g (46 mmoles) of strontium would be 9.2 kJ compared to the energy released over the 25 hours of reaction time of 257 kJ. Thus, an excess power of 2.85 W measured calorimetrically on rt-plasmas with Sr^+ and Ar^+ as catalysts and atomic hydrogen as a reactant, compared with controls with no hydrogen and no catalyst present was representative of the excess power. This observation supported the rt-plasmas mechanism since there is no known chemistry which could account for the observed power.

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Figure Captions

Figure 1. The experimental setup for generating an argon-hydrogen-strontium rt-plasma.

Figure 2. Air-gap reactor comprising a hollow anode DC glow discharge cell and a stainless steel jacket for maintaining an argon-hydrogen (95/5%)-Sr^+ plasma.

Figure 3. Water bath calorimetric system for measuring the power balance on an argon-hydrogen (95/5%)-Sr^+ plasma.

Figure 4. The 656.3 nm Balmer α line width recorded with a high-resolution visible spectrometer on the initial emission of a hydrogen-strontium rt-plasma and the emission at 70 hours of operation. Significant broadening was observed over time corresponding to an average hydrogen atom temperature of 20 eV.

Figure 5. (a) The emission spectrum from a hollow anode, glow discharge of argon-hydrogen (95/5%)-strontium showing an intense Sr^+ (407.77 nm) line. (b) The high resolution spectrum (653.0-659.0 nm) of the argon-hydrogen (95/5%)-strontium plasma emission showing selective broadening of the Balmer α line relative to the argon and strontium atomic lines. (c) The selectively broadened 656.3 nm Balmer α line width recorded with a high-resolution visible spectrometer corresponding to an average hydrogen hot atom temperature of 50.2 eV with a 83.5% population.

Figures 6. (a) Water bath temperature profiles of the air-gap reactor with an input power of 10 W to maintain an argon-hydrogen (95/5%)-Sr^+ plasma compared to the heater calibration. (b) Excess power obtained for the plasma reaction as a function of time.

Fig. 1

Gas inlet

Power feedthrough

Gas Outlet

1/4 in. SS tube

Type K TC

reactor

quartz rod

Contact flanges

Stainless steel
Jacket

Fig. 2

18

Fig. 3

Labels in figure:
- Baratron
- Mass Flow Controller
- Gas supply
- Stirrer
- Power supply
- thermistor
- To vacuum system with pressure gage and optional Ar backfill
- To vacuum pump
- TC
- Non-metal shaft
- De-ionized water
- Chamber
- Tank
- Styrofoam insulation
- Acrylic standoffs minimal contact

Fig. 4

20

Fig. 5a

21

Fig. 5b

22

Fig. 5c

23

Fig. 6a

24

Fig. 6b

25
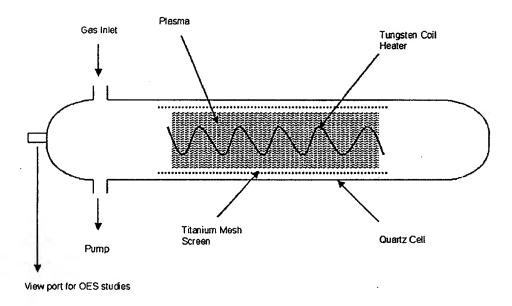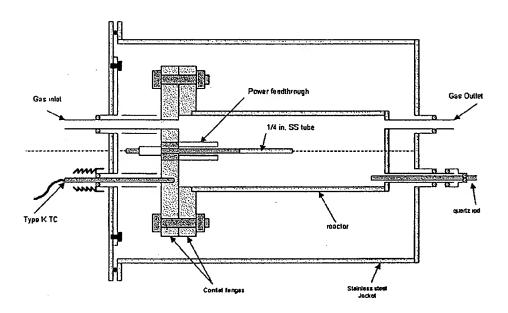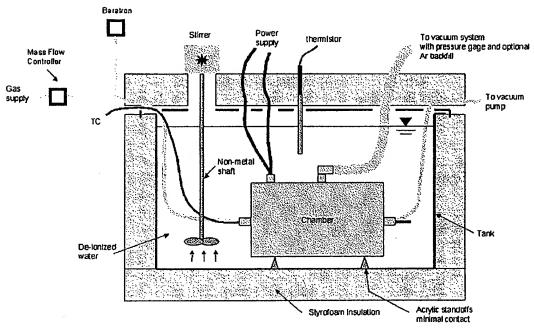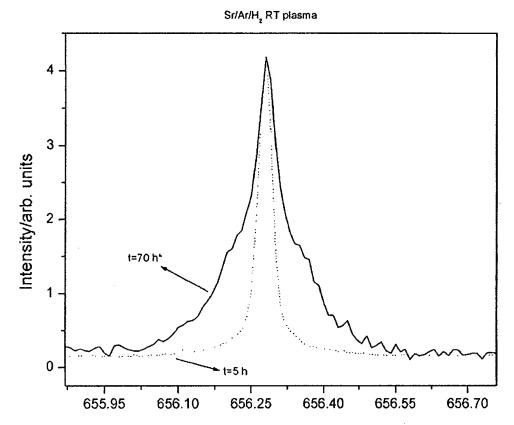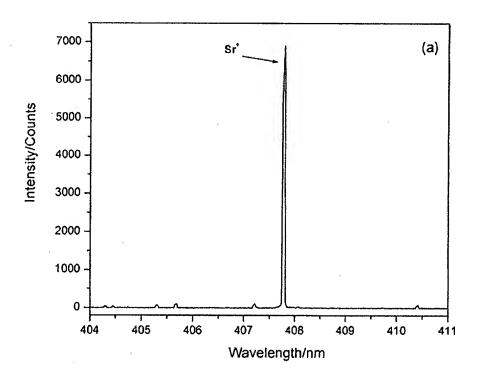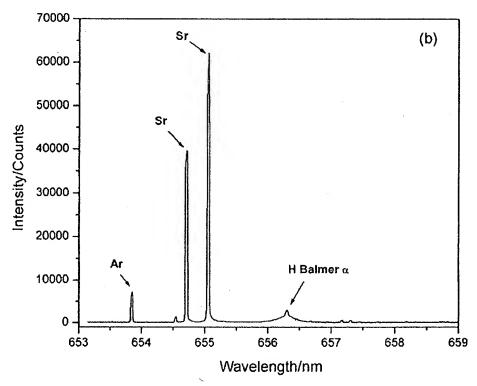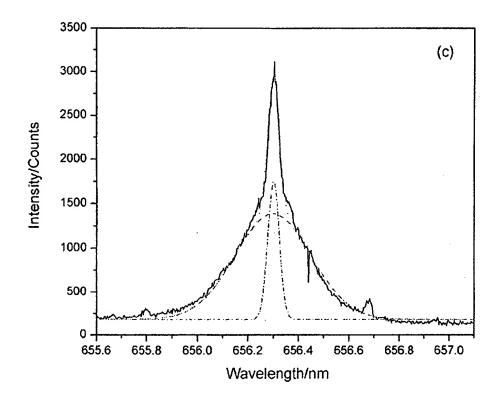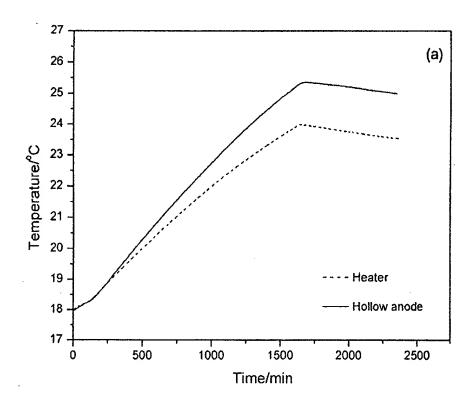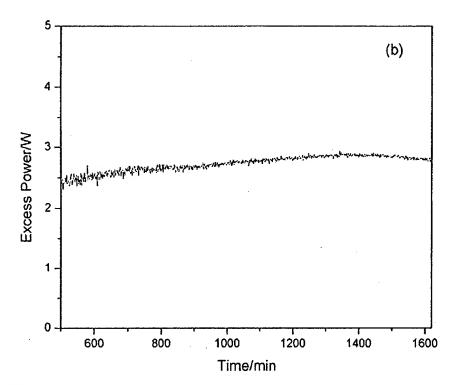
RECEIPT FROM PTO FOR INDICATED ITEMS

(Do NOT Use for New or Continuing Applications of Any Kind)
Use 2 postcards for all New AppIns. (Cont/Div/CIP, too)

Appln. No: 09/110,717	Attny: Jeff Melcher
First Inventor: Mills	Date: August 22, 2001
BATTERY, ELECTROLYTIC CELL, AND FUEL CELL	Matter No: 226-8AC6
	Client No: 27462

ENCLOSED:

☐ Response/Amendment ☐ Cover Sheet ☐ Cited/Listed

☐ Completion Request for R 53(f)/PCT Nat.

☐ No. of Pages Abstract

☐ No. of Pages Spec and Claims

☐ No. of Numbered Claims Only

☐ No. of Sheets of Drawings

☐ 1 Set ☐ 1 Set Informal ☐ Cover Letter

OIPE
AUG 2 2 2001
PATENT & TRADEMARK OFFICE

$ [_____] Fee (Check)

OTHER: Information Disclosure Statement

Current DUE DATE: **None**

(Submit Single Copy Only)

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re PATENT APPLICATION of   Group Art Unit: 1754
Inventor(s): Mills

App'n Ser. No.: 09/110,717   Examiner(s): Kalafut for the
                                            Secret Committee

Filing Date: 07/07/1998

Title: BATTERY, ELECTROLYTIC CELL, AND FUEL CELL

30 October 2007

INFORMATION DISCLOSURE STATEMENT

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

      Attached are copies of PTO/SB/O8A and B forms listing documents that were previously submitted. Also attached are copies of the stamped postcard receipts proving that the PTO/SB/O8A and B forms and listed documents were filed in the U.S. Patent Office.

      Applicant again requests full consideration of the foregoing enclosures, including return of a copy of the attached PTO/SB/08A and B forms with the Examiner's initials in the left column per MPEP § 609. All required fees have been paid. Furthermore, any previously filed information disclosure statement that was not considered for timeliness or fees should be considered in compliance with the Request for Continued Examination filed herewith.

                         Respectfully submitted,
                         Manelli Denison & Selter PLLC

By

                         Jeffrey S. Melcher
                         Reg. No.: 35,950
                         Tel. No.: (202) 261-1045
Customer No. 20736   Fax. No.: (202) 887-0336

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re <u>PATENT APPLICATION</u> of   Group Art Unit: 1754
Inventor(s): Mills

App'n Ser. No.: 09/110,717   Examiner(s): Kalafut for the
                                                        Secret Committee

Filing Date: 07/07/1998

Title: BATTERY, ELECTROLYTIC CELL, AND FUEL CELL

30 October 2007

INFORMATION DISCLOSURE STATEMENT

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

In connection with this Information Disclosure Statement, and others filed in this application, the undersigned and Applicant have made concerted efforts to cite in this application all relevant information that has come to their attention, either based on information in Applicant's own possession or provided by PTO officials responsible for examining his other pending cases. In furtherance of those efforts, the following description is provided of some of the actions they have taken to make all relevant information available to the PTO.

Regarding these matters, the undersigned and his co-counsel, Jeffrey A. Simenauer, have had numerous telephone discussions with Applicant regarding PTO requirements for disclosing relevant information relating to the prosecution of his patent applications. Counsel have also traveled twice in the past few years to visit assignee BlackLight Power Inc.'s business office and research facility in Cranbury, New Jersey and to meet with Applicant, Dr. Randell L. Mills and other BlackLight personnel, most recently on September 20, 2007. On both occasions, Counsel reminded Applicant of his duty of disclosure in connection with the requirements for submission of relevant information to the PTO in his pending patent applications. Counsel also advised

Applicant of recently implemented and proposed PTO rule changes and their potential impact on the prosecution of his cases. All relevant information that was brought to Counsel's attention during these and prior discussions of such matters has been made of record.

Due to the number of pending patent applications filed on behalf of Applicant, and the citation of various documents by different Examiners during the examination of those applications, Counsel have also undertaken extensive, periodic reviews of the application files in an effort to make certain that all such information has been submitted to the PTO in each case. Based on those reviews, Counsel have now prepared, and submit with this Information Disclosure Statement, a Master List representing what they believe to be a complete compilation of all information known to have been cited in Applicant's pending patent applications relating to his lower-energy hydrogen technology. This list includes what Counsel further believes to be irrelevant documents relating to "cold fusion," most of which were cited by the PTO in its attempt to associate Applicant's claimed invention with that controversial technology, which erroneous position it has not yet withdrawn. A copy of the Master List is provided in Attachment B.

Based on a comparison of this Master List to the documents cited in the present application, Applicant submits herewith those documents that have not yet been made of record. If there are any documents cited in one of Applicant's other pending cases that are not found on the Master List, or otherwise have not been submitted in this case, such omittance is inadvertent, as no references have been intentionally withheld. Given that all of Applicant's pending patent applications relating to his novel hydrogen technology have been consolidated under a single Examiner, Dr. Bernard Souw, Applicant believes that the PTO is already aware of all information cited in those cases and kindly requests that the Examiner bring to Applicant's attention any information which he knows is not already of record.

This collective treatment of the documents in Applicant's pending applications is consistent with the PTO's present handling of documents, as indicated by Paper No.

20070918 recently filed on September 18, 2007, in U.S. App'n Ser. No. 08/467,911, which includes "Master List of Prior Art Cited in Hydrocatalysis Cases" prepared by the PTO. The citation of that Master List further indicates that the PTO has consolidated all of Applicant's patent applications assigned to his company, BlackLight Power, Inc. (previously known as "Hydrocatalysis"), and that, at least to some extent, it has been tracking and considering all documents cited in those cases. Thus, even though the PTO is already aware of those documents, Applicant and his Counsel have used their best efforts to independently compile and submit all of that information in this case.

Applicant further notes that in all of Applicant's pending applications relating to his lower-energy hydrogen technology, the PTO has made similar rejections under 35 U.S.C. §§ 101 and 112. While different named Examiners are listed in each application, the record shows that Dr. Souw has prepared numerous Appendices and arguments that have been incorporated into Office Actions in all of Applicant's pending applications, including a Consolidated Appendix. Due to the large amount of information illicited and requested by the PTO, to assist the Examiners, Applicant has provided a detailed response summarizing and organizing all submitted arguments, experimental evidence, and the file history, as well as a copy of his detailed response to the Consolidated Appendix, in all of his pending patent applications relating to lower-energy hydrogen technology. No relevant information from any pending application relating to lower-energy hydrogen technology has been intentionally withheld by Applicant from his other pending applications.

Regarding Applicant's submitted and published journal articles, the undersigned has also made every effort to ascertain the latest information regarding which of those articles were posted on the Internet at BlackLight's website and when that posting occurred. A complete, updated listing of articles is provided herewith, which includes this information. Thus, for those articles that were disclosed on the Internet before completion of the peer-review process, the "Internet publication date" has also been included.

Other supplemental information for the PTO's consideration is also being

provided herewith based on new information that has recently come to the undersigned's attention in connection with Dr. Phillips' ownership of stock options in BlackLight Power, Inc. Dr. Phillips' prior ties to BlackLight have already been disclosed to the PTO in his Rule 132 Declarations and should be self-evident based upon his being listed as a co-inventor on the face of BlackLight's U.S. Patent No. 6,024,935. To ensure full disclosure, however, the undersigned has advised BlackLight to make that information available and to identify any business or financial relationships it has with any other persons and/or entities that have been involved in generating evidence or preparing articles submitted to the PTO for consideration. BlackLight has provided the undersigned with a list of this information, which is appended hereto as Attachment A. This Attachment was prepared by BlackLight personnel, including its controller and accountant, after extensive searches of the company's financial documents and other records. If there are any persons and/or entities not on the list that should have been included, such omission is inadvertent, as no such information has been intentionally withheld.

Also attached hereto are PTO/SB/08A and B forms listing information being submitted. While some of the PTO/SB/08A and B forms filed herewith, and in previous submissions, may refer to "prior art," that should not be taken as an admission that the listed information is in fact prior art. Applicant has not limited his submissions to prior art, but rather, has also included other documents and information thay may have a bearing on this case. To cite just one example, the PTO required Applicant to list his published articles on PTO/SB/08 forms even though Applicant notified the PTO officials imposing this requirement that those articles did not constitute prior art in relation to all of his pending patent applications.

This Information Disclosure Statement is being filed with a Request for Continued Examination and, thus, is timely filed. No further fees are required. Consideration of the foregoing remarks and enclosures, including return of a copy of the attached PTO/SB/08A and B forms with the Examiner's initials in the left-hand column per MPEP § 609, and an early action on the merits of this application are earnestly solicited.

Respectfully submitted,
Manelli Denison & Selter PLLC

By

Jeffrey S. Melcher
Reg. No.: 35,950
Tel. No.: (202) 261-1045
Fax. No.: (202) 887-0336

Customer No. 20736

PTO/SB/08A (Modified)

Substitute for form 1449A/PTO

OCT 3 0 2007

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(use as many sheets as necessary)

Sheet	1	of	3 /

Complete if Known	
Application Number	09/110,717
Filing Date	07/07/1998
First Named Inventor	Mills
Group Art Unit	1745
Examiner Name	Kalafut
Attorney Docket Number	

U.S. PATENT DOCUMENTS

Examiner Initials*	Cite No.[1]	U.S. Patent Document Number	Kind Code[w] (if known)	Name of Patentee of Applicant of Cited Document	Date of Publication of Cited Document MM-DD-YYYY	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		3,253,884		Jung, et al.	05-31-1966	
		3,462,622		Cann et al.	08-1969	
		4,000,036		Ensley	12-1976	
		4,095,118		Rathbun	06-1978	
		4,149,931		Christensen	04-1979	
		4,155,712		Taschek	05-22-1979	
		4,202,004		Anderson	05-1980	
		4,337,126		Gilligan, III et al.	06-29-1982	
		4,353,871		Bartilt, et al.	10-12-1982	
		4,464,990		Bendler	08-14-1984	
		4,488,490		Betts	12-18-1984	
		4,694,755		Ibarra	10-22-1987	
		4,702,894		Cornish	10-27-1987	
		4,792,725		Levy et al.	12-1988	
		4,808,286		Angelo, II	02-28-1989	
		4,957,727		Bogdanovic	09-18-1990	
		5,273,635		Gernert	12-28-1993	
		5,449,434		Hooke et al.	09-1995	
		5,577,090		Moses	11-1996	

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] Unique citation designation number. [2] See attached Kinds of U.S. Patent Documents. [3] Enter Office that issued the document, by the two-letter code (WIPO Standard ST. 3) [4] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [5] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST. 16 if possible. [6] Applicant is to place a check mark here if English language Translation is attached.

PTO/SB/08A (Modified)

Substitute for form 1449A/PTO				Complete if Known	
INFORMATION DISCLOSURE STATEMENT BY APPLICANT *(use as many sheets as necessary)*				Application Number	09/110,717
				Filing Date	07/07/1998
				First Named Inventor	Mills
				Group Art Unit	1745
				Examiner Name	Kalafut
Sheet	2	of	З/	Attorney Docket Number	

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		5,593,640		Long, et al.	01-14-1997	
		5,669,975		Ashtiani	09-1997	
		5,761,481		Kadoch et al.	06-1998	
		5,789,744		Spence, et al.	08-04-1998	
		5,801,971		Ohta	09-1998	
		5,819,073		Nakamura	10-1998	
		5,838,760		Moses	11-1998	
		5,864,322		Pollon et al.	01-1999	
		5,883,005		Minton et al.	03-1999	
		5,888,414		Collins et al.	03-1999	
		5,969,470		Druz et al.	10-1999	
		6,024,935		Mills, et al.	02-15-2000	
		6,064,154		Crouch et al.	05-2000	
		6,149,829		Takamatsu et al.	11-2000	
		6,150,755		Druz et al.	11-2000	
		6,151,532		Barone et al.	11-2000	

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	Application Number	09/110,717
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	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut
Sheet 3 of *31*	Attorney Docket Number	

U.S. PATENT DOCUMENTS

Examiner Initials*	Cite No.[1]	U.S. Patent Document		Name of Patentee of Applicant of Cited Document	Date of Publication of Cited Document MM-DD-YYYY	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		Number	Kind Code[W] (if known)			
		6,444,137		Collins et al.	09-2002	
		6,551,939		Takamatsu et al.	04-2003	
		6,579,465		Takamatsu et al.	06-2003	
		6,690,705		Maksimov et al.	02-2004	
		7,188,033		Mills	03-06-2007	
		2001/0007725		Faris et al.	07-2001	
		2001/0008803		Takamatsu et al.	07-2001	
		2002/0133326		Chung et al.	09-2002	

Examiner Signature		Date Considered	

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PTO/SB/08A (Modified)

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	Application Number	09/110,717
INFORMATION DISCLOSURE STATEMENT BY APPLICANT	Filing Date	07/07/1998
	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut

Sheet	4	of	Э/	Attorney Docket Number	

FOREIGN PATENT DOCUMENTS

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		Office[3]	Number[4]	Kind Code[5] (if known)				
		WO	99/05735	A1	Mills	03-04-1999		
		WO	99/26078	A1	Mills	5-27-1999		
		WO	99/34322	A1	Mills	7-8-1999		
		WO	99/35698	A3	Mills	07-15-1999		
		WO	00/07931	A1	Mills	02-17-2000		
		WO	00/07932	A2	Mills	2-17-2000		
		WO	00/25320	A1	Davies	05-04-2000		
		WO	01/095944	A2	Mills	12-20-2001		
		WO	01/18948	A1	Mills	3-15-2001		
		WO	01/21300	A2	Mills	03-29-2001		
		WO	01/22472	A2	Mills	3-29-2001		
		WO	01/70627	A3	Mills	08-27-2001		
		WO	02/08787	A2	De Geus	01-31-2002		

Examiner Signature		Date Considered	

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		Filing Date	07/07/1998
		First Named Inventor	Mills
		Group Art Unit	1745
		Examiner Name	Kalafut
Sheet	5	of	3/	Attorney Docket Number	

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		Office[3]	Number[4]	Kind Code[5] (if known)				
		WO	02/087291	A2	Mills	10-31-2002		
		WO	02/088020	A2	Mills	11-7-2002		
		WO	02/16956	A1	Mills	2-28-2002		
		WO	03/093173	A2	Mills	11-13-2003		
		WO	03/066516	A2	Mills	8-14-2003		
		WO	04/092058	A2	Mills	10-28-2004		
		WO	05/041368	A2	Mills	10-6-2005		
		WO	05/067678	A2	Mills	7-28-2005		
		WO	2005/116630	A1	Mills	12-08-2005		
		WO	2007/051078	A1	Mills	05-03-2007		
		WO	2007/053486	A1	Mills	05-10-2007		
		GB	2 343 291		Lloyd Wise, Tregear & Co	05-13-2000		
		JP	2002008892A		Shimazu	01-2002		

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Substitute for form 1449B/PTO	Complete if Known	
	Application Number	09/110,717
INFORMATION DISCLOSURE STATEMENT BY APPLICANT	Filing Date	07/07/1998
	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut

| Sheet | 6 | of | ∂ / | Attorney Docket Number | |

OTHER PRIOR ART — NON PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No. [1]	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T[2]
		S. Aaronson, "Hydrino Theory: Which Overturns Quantum Theory, Is in Turn Overturned by Doofusino Theory," <http://www.scottaaronson.com/writings/doofusino.html>	
		"Atomic Physics Progress Report 1995-1996" (internet page) atompc2.fysik.lth.se/AFDOCS/Progrep956/contents.asp (author and date unknown)	
		"Atomic Spectroscopy" (internet page) physics.nist.gov/Pubs/AtSpec/node20.html (author and date unknown)	
		Baard, Erik. "The Empire Strikes Back." *The Village Voice*, April 26-May 2, 2000	
		Baard, Erik. "Quantum Leap." *The Village Voice*, Dec 22-28, 1999.	
		Baard, Erik. "Researcher Claims Power Tech That Defies Quantum Theory." *Dow Jones Newswires*, Oct 6, 1999.	
		Baard, Erik, "Hydrino Theorist Gets Nod From NASA-Funded Investigation Eureka?", *The Village Voice*, Dec. 6, 2002	
		Barmann et. al. "Spatially and Temporally Resolved Studies of the Electron Density in Liquid Streamers by Emission Spectroscopy" (Internet page) atompc2.fysic.lth.se/AFDOCS/Progrep956/5al.htm (Atomic Physics Progress Report) (1995-1996)	
		R. W. Bass, "Email from Bob Bass to Randell Mills," August 6, 2000.	
		Beiser, A. *Concepts of Modern Physics*, Fourth Edition, McGraw-Hill Book Company, New York, 1978, p. 407.	

Examiner Signature		Date Considered	

Substitute for form 1449B/PTO			Complete if Known	
INFORMATION DISCLOSURE STATEMENT BY APPLICANT *(use as many sheets as necessary)*			Application Number	09/110,717
			Filing Date	07/07/1998
			First Named Inventor	Mills
			Group Art Unit	1745
			Examiner Name	Kalafut
Sheet	7	of 9 *1*	Attorney Docket Number	

OTHER PRIOR ART — NON PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No. [1]	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T^2
		"The Biggest Venture Capital Conference of the Year is Quickly Approaching," Special to Evening Bullitin 09/29/2006, <http://www.theeveningbulletin.com/site/news.cfm?newsid=17263371&BRD=2737&PAG=461	
		"Blacklight Power - do they have something significant?" (internet page) www.phact.org/e/blp.htm (author and date unknown)	
		Blacklight Power, Inc., "Second Shareholder Newsletter '97" <http://web.archive.org/web/19980212141859/blacklightpower.com/sharenews2.html>	
		Blochinzew, *Grundlagen Der Quantenmechanik*, Veb Deutscher Verlag Der Wissenschaften, 1967	
		Boniface, et. al. "Calorimetry for a Ni/K_2CO_3 Cell." AECL Research, June 1994.	
		Bradford. "A Calorimetric Investigation of the Reaction of Hydrogen with Sample PSU #1." A Confidential Report submitted to Hydrocatalysis Power Corporation, September 1994.	
		Brewer, Shelby T. Book review of "The grand Unified Theory of Classical Quantum Mechanics (Hardcover) by Randell L., Dr. Mills." (internet page) http://www.amazon.com/gp/product/product-description/0963517139/ref=dp_proddesc_0/103-5711659-8507030 (date unknown)	
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT	Filing Date	07/07/1998
	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut

| Sheet | 8 | of | *Ɔ/* | Attorney Docket Number | |

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(use as many sheets as necessary)			Examiner Name	Kalafut
Sheet	9	of _2l_	Attorney Docket Number	

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		Group Art Unit	1745
		Examiner Name	Kalafut
Sheet	10	of	⊃/	Attorney Docket Number	

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				Group Art Unit	1745
				Examiner Name	Kalafut
Sheet	11	of	∂/	Attorney Docket Number	

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	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut
Sheet	12	of	31	Attorney Docket Number	

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			First Named Inventor	Mills
			Group Art Unit	1745
			Examiner Name	Kalafut
Sheet	13	of ラ/	Attorney Docket Number	

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	First Named Inventor	Mills
	Group Art Unit	1745
	Examiner Name	Kalafut

Sheet	14	of	_3 1_	Attorney Docket Number	

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	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut
Sheet	15	of	_9/_	Attorney Docket Number	

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			Group Art Unit	1745
			Examiner Name	Kalafut
Sheet	16	of 𝟥𝟣	Attorney Docket Number	

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Examiner Name	Kalafut
Attorney Docket Number	

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(use as many sheets as necessary)

Sheet	17	Of	3/

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	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut

Sheet	18	of	3 /	Attorney Docket Number	

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	Filing Date	07/07/1998
	First Named Inventor	Mills
	Group Art Unit	1745
	Examiner Name	Kalafut

Sheet	19	of	♂/	Attorney Docket Number	

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		Group Art Unit	1745
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Sheet	20	of ⊃ /	Attorney Docket Number	

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Sheet	21	of	Ƽ/	Attorney Docket Number	

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Sheet 22 of 9/	Attorney Docket Number	

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Sheet	23	of	*91*	Attorney Docket Number	

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Sheet	24	of	9/	Attorney Docket Number	

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| Sheet | 26 | of | 3 1 | Attorney Docket Number | |

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Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] Unique citation designation number. [2] Applicant is to place a check mark here is English language Translation is attached.

Substitute for form 1449B/PTO			**Complete if Known**	
INFORMATION DISCLOSURE STATEMENT BY APPLICANT			Application Number	09/110,717
			Filing Date	07/07/1998
			First Named Inventor	Mills
			Group Art Unit	1745
(use as many sheets as necessary)			Examiner Name	Kalafut
Sheet	30	of 𝟥𝟣	Attorney Docket Number	

OTHER PRIOR ART — NON PATENT LITERATURE DOCUMENTS			
Examiner Initials*	Cite No. [1]	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T[2]
		4. Mills et al., "Fractional Quantum Energy Levels of Hydrogen," Fusion Technology, Vol. 28, No. 4, November, (1995), pp. 1697–1719. (Internet Publication Date: Nov. 1, 2001.)	
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Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

PTO/SB/08B (Modified)

Substitute for form 1449B/PTO	Complete if Known	
	Application Number	09/110,717
INFORMATION DISCLOSURE STATEMENT BY APPLICANT	Filing Date	07/07/1998
	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut
Sheet	31	of	𝒶/	Attorney Docket Number	

OTHER PRIOR ART — NON PATENT LITERATURE DOCUMENTS			
Examine r Initials*	Cite No. ¹	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T²
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Examiner		Date	

ATTACHMENT A		Date(s)	Compensation Arrangements	Cash Payments Made	Options Issued	Shares Owned
AKHTAR (Employee)	Dr. Kamran	-	Employee Salary	-	EE Options Only	None
BALDWIN (NASA)	Dr. R.	-	-	-	None	None
BONIFACE (Chalk River Labs)	Dr. H.A.	-	-	-	None	None
BRADFORD (PSU Student)	Dr. Michael	9/13/1994	Ad Hoc/ One-time Only	9/13/1994	None	None
CHANG (Employee)	Dr. Zhixiang	-	Employee Salary	-	EE Options Only	None
CHEN (EE & Consultant)	Dr. Chun-Ku	6/1/04-5/31/05	$50/hour	2/7/2005	EE Options Only	None
CHEN (Employee)	Dr. Xuemin	-	Employee Salary	-	EE Options Only	None
CLARK (INP Greifswald)	Dr. H.R.	-	-	-	None	None
CONRADS (INP Greifswald transferred agrmnt to Conrads)	Dr. Johannes	8/4/99-9/23/05	2 wire transfers	2/14/00 6/12/01	Options granted from 9/9/96 to 8/5/97; some options expired; some options exercised 9/7/06	Some options exercised 9/7/06
CRAIG	Dr. W.Y.	-	-	-	None	None
CRAW-IVANCO (Chalk River Labs)	Dr. M.T.	-	-	-	None	None
DAYALAN (Employee)	Dr. Ethirajulu	-	Employee Salary	-	EE Options Only	None
DHANDAPANI (Employee)	Dr. Bala	-	Employee Salary	-	EE Options Only	None
DONG (EE & Consultant)	Dr. Jinquan	7/30/03-1/31/04 2/1/04-7/31/04 11/16/04-5/1/505	$35/hour $45/hour $45hour	2/28/02 8/20/03	EE Options Only	None
ECHEZURIA (Employee)	Alejandra	-	Employee Salary	-	EE Options Only	None
FRALICK (Semitech)	Dr. G.C.	-	-	-	None	None
FUELLING (U Nevada)	Dr. Stephan	-	-	-	None	None
GAMBERALE	Luca	-	-	-	None	None
GERNERT (Thermacore)	Dr. N.J.	-	-	-	None	None
GOOD (EE & Officer)	William	-	Employee Salary	-	EE & Officer Options Issued Beginning 9/1/92	Shares Owned Beginning 1991

Name (Affiliation)	First Name	Dates	Rate	Dates	Options	Shares
GREENIG (EE & Consultant)	Nelson	11/1/01-10/31/02 11/1/02-10/31/03 3/8/04-3/7/05 3/8/05-3/7/06 3/8/06-3/7/07 3/8/07-3/7/08	$50/hour $50/hour $50/hour $50/hour $50/hour $50/hour	7/19/95 4/27/01 10/14/02	EE Options Only	None
HALDEMAN (MIT Lincoln Labs)	Dr. C.W.	-	-	-	None	None
HE (Employee)	Dr. Jiliang	-	Employee Salary	-	EE Options Only	None
HICKS (Employee)	Steven	-	Employee Salary	-	EE Options Only	None
HILBORN (Chalk River Labs)	Dr. J.W.	-	-	-	None	None
ISELER (MIT Lincoln Labs)	Dr. G.W.	-	-	-	None	None
JACOX (INEL)	Dr. Michael	-	-	-	Options granted 9/9/96 to 3/3/97; all options expired	None
JANSSON (Rowan U)	Dr. Peter M.	6/10/02-10/31/02 (contract)	$100 $10	10/17/97 12/31/2002	None	Purchased shares 7/2/97; gifted to ex-wife and son 5/1/07
KNEIZYS	S.	-	-	-	None	None
KRYUKOV (Moscow Power Engineering Institute)	Dr. A.P.	-	-	-	None	None
KURTZ (PSU)	Dr. Stewart	-	-	-	Options granted 9/9/96 to 11/8/02; some expired	None
LEE (U of Ohio)	Dr. Jang-Jung	-	-	-	None	None
LU (EE & Consultant)	Dr. Ying	8/6/01 5/9/03-5/16/03 5/27/03-5/30/03 5/30/03-6/30/03 7/1/03-7/31/03 8/1/03-1/30/04	$100/hour $80/hour $80/hour $45/hour $45/hour $45/hour	10/01/01 5/23/03	EE Options Only	None
MARCHESE (Rowan U)	Dr. Anthony J.	6/10/02-10/31/02 (contract)	$10 non-material	12/31/2002	None	None
MAYO (EE & Consultant)	Dr. Robert	6/8/01-8/8/01	$50/hour	7/23/2001	EE Options Only	None
MEYERS (NASA)	Dr. I.	-	-	-	None	None
MILLER (Lehigh U)	Dr. Alfred	-	$250	6/12/1997	Options granted 9/9/96 to 3/3/97; all options expired	None

					EE & Director Options Issued Beginning 9/9/96	Shares Owned Beginning 1991
MILLS (EE & Director)	Dr. Randell	-	Employee Salary	-		
NANSTEEL (EE & Consultant)	Dr. Mark W.	3/30/05-3/29/06 3/30/06-3/29/07 3/30/07-8/31/08	$80/hour $80/hour $80/hour	8/24/2005	EE Options Only	None
NESTEROV (Moscow Power Engineering Institute)	Dr. S.B.	-	-	-	None	None
NIEDRA (NASA)	Dr. J.	-	-	-	None	None
NONINSKI (Brookhaven)	Dr. V.	-	-	-	None	None
ONUMA (Employee)	Dr. Takeyoshi	-	Employee Salary	-	EE Options Only	None
PACIFICORP		-	-	-	Options granted 4/7/97 to 4/27/98; some options expired	Purchased shares 9/20/96 & 7/2/97; transferred all shares to ScottishPower Ventures, Inc. 6/21/07
PETERSON (Westinghouse)	Dr. S.H.	-	-	-	None	None
PHILLIPS (PSU,UNM,LANL)	Dr. Jonathan	2/1/96-1/31/97 1/1/97-4/30/97 3/15/00-3/18/00 10/8/01-4/8/02 4/8/02-10/8/02 10/9/02-10/8/03 10/9/03-10/8/04 10/9/04-10/8/05 10/9/05-10/8/06 10/9/06-10/807	$100/hour Options Only $5,000 $125/hour $125/hour $125/hour $100/hour $100/hour $100/hour $100/hour	4/26/95 5/9/00	Options granted 9/9/96-1/14/06; some options exercised	Some options exercised 9/1/06 & 2/20/07
RAY (Employee)	Dr. Paresh	-	Employee Salary	-	EE Options Only	None
SANKAR (EE & Consultant)	Dr. Jayasree	3/17/03-3/16/04 3/22/04-3/21/05	$50/hour $50/hour	-	EE Options Only	None
SAVOYE (MIT Lincoln Labs)	Dr. G.W.	-	-	-	None	None
SCHARER (U Wisconsin)	Dr. John	1/5/05-1/4/06 1/5/06-1/4/07 1/5/07-1/4/08	$800/day $100/hour $110/hour	11/14/2005	None	None
SCHMALZEL (Rowan U)	Dr. John L.	6/10/02-10/31/02	$10 (contract) non-material	12/31/2002	None	None
SHANNON (Employee)	Tina	-	Employee Salary	-	EE Options Only	None
SHAUBACH (Thermacore)	Dr. R.M.	-	-	-	None	None
SIMMONS (Lehigh U)	Dr. G.	-	-	-	None	None
TREMBLAY (Chalk River Labs)	Dr. R.P.	-	-	-	None	None

TURNER (Spectral Data)	Dr. Gary L.	-	-	-	None	None
VOIGT (EE & Consultant)	Dr. Andreas ▮▮▮	8/27/04-8/26/05	$50/hour	-	EE Options Only	None
WATTS (INEL)	Dr. K.D.	-	-	-	None	None
WEISMANN	Dr. H.	-	-	-	None	None
WIESMANN	Dr. H.	-	-	-	-	-
WRUBEL (INP Greifswald)	Dr. Th.	-	-	-	None	None
ZEA (Employee)	Dr. Hugo	-	Employee Salary	-	EE Options Only	None

ATTACHMENT B

MASTER LIST OF CITED AND SUBMITTED DOCUMENTS

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Foreign Patent Document			Name of Patentee or Applicant of Cited Document	Date of Publication of Cited Document MM-DD-YYYY	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear	T[6]
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Letter from Senator Jon S. Corzine to The Honorable Todd Q. Dickinson with attachments, August 2, 2001 (see Attachment O)
Letter from Senator Max Cleland to Ms. Jane Cooksey with attachments, March 24, 2000 (see Attachment O)
Letter from Senators Max Cleland and Ron Wyden to Chairman Patrick Leahy, December 20, 2001 (see Attachment O)
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re PATENT APPLICATION of
Inventor(s): Mills

Group Art Unit: 1745

Appln. No.: 09/110,717

Examiner: Kalafut

Filing Date: 7/7/1998

Title: BATTERY, ELECTROLYTIC CELL, AND FUEL CELL

*   *   *   *   *

August 22, 2001

INFORMATION DISCLOSURE STATEMENT

Hon. Commissioner of Patents
 and Trademarks
Washington, D.C. 20231

Sir:

Attached are PTO/SB/O8 B forms listing the enclosed documents.   These

documents were uncovered and utilized by Applicant as background material in

preparing experimental evidence requested by the U.S. Patent and Trademark Office

("PTO").   None of the cited documents disclose or teach Applicant's lower-energy

hydrogen technology.

Applicant hereby petitions the PTO to consider this information disclosure

statement in accordance with 37 C.F.R. § 1.97.

To the best of the undersigned's and applicant's knowledge, we were not aware

of these documents before mid-July 2001. It should be pointed out, however, that over

the course of the twelve-plus years of researching and developing Applicant's lower-

energy hydrogen technology, Applicant has cited an extraordinary number of articles in

the many papers and books he has written. Thus, we cannot be absolutely certain that we were unaware of all of the enclosed documents for more than three months. With this understanding after making a "reasonable inquiry" as required by Rule 97(e)(2), I hereby certify that, to my knowledge, no item of information contained in the Information Disclosure Statement filed herewith was known to any individual designated in Rule 56(c), including Applicant and the undersigned, for more than three months prior to the date of filing of this Information Disclosure Statement in the PTO. I further certify that no item of information contained in the Information Disclosure Statement filed herewith was cited in a communication from a foreign patent office in a counterpart foreign application.

Applicant further submits that the final Office Action entered in this case is improper and a petition to remove the improper finality will be filed shortly. Thus, if the finality is removed, no petition fee would be necessary and the enclosed documents should then be fully considered under Rule 97(c). If a petition fee is required, please charge any deficiency to our Deposit Account No. 50-0687 under Order No. 62-226 for which purposes this paper is submitted in duplicate.

This Information Disclosure Statement is intended to be in full compliance with the rules, but should the Examiner find any part of its required content to have been omitted, prompt notice to that effect is earnestly solicited, along with additional time under Rule 97(f), to enable Applicant to fully comply. Consideration of the foregoing and enclosures plus the return of a copy of the herewith PTO/SB/08B forms with the

Examiner's initials in the left column per MPEP § 609 along with an early action on the

merits of this application, are earnestly solicited.

Respectfully submitted,

Manelli Denison & Selter PLLC

By _____

Jeffrey S. Melcher
Reg. No.: 35,950
Tel. No.: (202) 261-1045
Fax. No.: (202) 887-0336

Customer No. 20736

Substitute for form 1449B/PTO	Complete if Known	
INFORMATION DISCLOSURE STATEMENT BY APPLICANT	Application Number	09/110,717
	Filing Date	7/7/98
	First Named Inventor	Mills
	Group Art Unit	1745
(use as many sheets as necessary)	Examiner Name	Kalafut

| Sheet | 1 | of | 3 | Attorney Docket Number | |

OTHER PRIOR ART — NON PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No. [1]	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T[2]
		ABELÈS, Ed., Chapter 9, "Structure of Trapped Electron and Trapped Hole Centers in Alkali Halides 'Color Centers'", *Optical Properties of Solids*, 1972, pp. 718-754, North-Holland Publishing Company, Amsterdam	
		DELBECQ et al., "Pragmatic Resonance Investigation of Irradiated KCI Crystals Containing *U*-Centers", *Phys. Rev.*, Nov. 1, 1956, **104**, pp. 599-604	
		DÖTSCH et al., "Localized Vibrations of H and D Ions in NaF and LiF", *Solid States Communications*, 1965, **3**, pp. 297-298	
		RAUCH et al., "Some *F*-Band Optical Oscillator Strengths in Additively Colored Alkali Halides", *Physical Review*, Feb. 1, 1957, **105**, pp. 914-920	
		FISCHER et al., "Sh-, S Und S$^-$Zentren In KC1-Kristallen", *Physics Letters,* Oct. 27, 1964, **13**, pp. 113-114	
		FRIED et al., "Solution for the Two-Electron Correlation Function in a Plasma", *The Physical Review*, Apr. 1, 1961, **122**, pp. 1-8	
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		KERKHOFF, "Zum photochemischen Verhalten sauerstoffhaltiger Komplexe in Alkalihalogenidkristallen", *Zeitschrift für Physik*, 1960 **158**, pp. 595-606	

Examiner Signature		Date Considered	

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				Examiner Name	Kalafut
Sheet	2	of	3	Attorney Docket Number	

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		FISCHER, "Die optische Absorption der U_2-Zentren in Alkalihalogeniden des BaCl-Typs", *Zeitschrift für Physik*, 1967, **204**, pp. 351-374	
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		HILSCH, "Eine neue Lichtabsorption in Alkalihalogenidkristallen", *Fachgruppe II*, pp. 322-328	
		FRITZ, "Anionlücken und Zwischengitterionen in Alkalihalogenid-Alkalihydrid-Mischkristallen", *J. Phys. Chem. Solids*, 1962, **23**, pp. 375-394, Pergamon Press, Great Britain	

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	Group Art Unit	1745
	Examiner Name	Kalafut
Sheet 3 of 3	Attorney Docket Number	

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		SCHAEFER, "Das Ultrarote Spektrum Des *U*-Zentrums", *Phys. Chem. Solids*, 1960, **12**, pp. 233-244, Pergamon Press, Great Britain	
		LÜTY, "Über Die Natur Der V_3-Zentren In Strahlungsverfärbtem KCCl", *J. Phys. Chem. Solids*, 1962, **23**, pp. 677-681, Pergamon Press, Great Britain	

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Copies of Documents Listed on SB08A and B Filed in:

U.S. Serial No.: 09/110,717   Inventor: Mills   Filing Date: 07/07/1998

Examiner: Kalafut   Art Unit: 1745   08AC6

Today's Date: 30 October 2007

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Atomic Physics Progress Report

1995 - 1996

- ## Introduction

  - ### Staff

- ## Basic Atomic Physics

  - ### High-order harmonic generation

    - Fundamental studies of high-order harmonics and optimisation of the harmonic source
    - Towards attosecond pulse generation using high-order harmonics

  - ### X-ray laser related investigations
  - ### Generation of hard X-rays from laser-produced plasmas
  - ### Clusters in intense laser fields
  - ### Time-resolved laser spectroscopy in the short-wavelength spectral region
  - ### Theoretical atomic physics
  - ### References

- ## Applied Optics and Quantum Electronics

  - ### Soft X-ray sources and applications

    - Liquid-target laser-plasma source
    - Applications

  - ### Non-intrusive scanning near-field microscopy
  - ### Photon echoes in rare-earth-ion-doped crystals, time-domain optical storage and processing

    - Erasure of photon-echo data
    - Homogeneous dephasing processes in rare-earth-ion-doped inorganic crystals
    - International co-operation

  - ### References

- ## Environmental Monitoring

- **Basic courses**
- **Specialised courses**
- **Master's Projects**

o **Graduate teaching**

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Atomic Spectroscopy

A Compendium of Basic Ideas, Notation, Data, and Formulas

20. Spectral Line Shapes, Widths, and Shifts

Observed spectral lines are always broadened, partly due to the finite resolution of the spectrometer and partly due to intrinsic physical causes. The principal physical causes of spectral line broadening are Doppler and pressure broadening. The theoretical foundations of line broadening are discussed in *Atomic, Molecular, & Optical Physics Handbook*, Chaps. 19 and 57, ed. G.W.F. Drake (AIP, Woodbury, NY, 1996).

- ### Doppler Broadening

  Doppler broadening is due to the thermal motion of the emitting atoms or ions. For a Maxwellian velocity distribution, the line shape is *Gaussian*; the full width at half maximum intensity (FWHM) is, in Å,

$$\Delta\lambda^{D}_{1/2} = (7.16 \times 10^{-7})\,\lambda(T/M)^{1/2} \quad . \tag{40}$$

  T is the temperature of the emitters in K, and M the atomic weight in atomic mass units (amu).

- ## Pressure Broadening

  Pressure broadening is due to collisions of the emitters with neighboring particles [see also *Atomic, Molecular, & Optical Physics Handbook*, Chaps. 19 and 57, ed. by G.W.F. Drake (AIP, Woodbury, NY, 1996)]. Shapes are often approximately Lorentzian, i.e.,
  $I(\lambda) \propto \{1 + [(\lambda - \lambda_0)/\Delta\ \lambda_{1/2}]^2\}^{-1}$. In the following formulas, all FWHM's and wavelengths are expressed in Å, particle densities N in cm^{-3}, temperatures T in K, and energies E or I in cm^{-1}.

  Resonance broadening (self-broadening) occurs only between identical species and is confined to lines with the upper or lower level having an electric dipole transition (resonance line) to the ground state. The FWHM may be estimated as

$$\Delta\lambda^{R}_{1/2} \simeq 8.6 \times 10^{-30}(g_i/g_k)^{1/2}\lambda^2\,\lambda_r\,f_r\,N_i \quad . \tag{41}$$

  where λ is the wavelength of the observed line. f_r and λ_r are the oscillator strength and wavelength of the resonance line; g_k and g_i are the statistical weights of its upper and lower levels. N_i is the ground state number density.

For the $1s2p\ ^1P^o_1$ - $1s3d\ ^1D_2$ transition in He I [$\lambda = 6678.15$ Å; λ_r $(1s^2\ ^1S_0 - 1s2p\ ^1P^o_1) =$ 584.334 Å; $g_i = 1$; $g_k = 3$; $f_r = 0.2762$] at $N_i = 1 \times 10^{18}$ cm^{-3}: $\Delta\lambda^R_{1/2} = 0.036$ Å.

Van der Waals broadening arises from the dipole interaction of an excited atom with the induced dipole of a ground state atom. (In the case of foreign gas broadening, both the perturber and the radiator may be in their respective ground states.) An approximate formula for the FWHM, strictly applicable to hydrogen and similar atomic structures only, is

$$\Delta\lambda^W_{1/2} \simeq 30 \times 10^{16}\ \lambda^2\ C_6^{2/5}(T/\mu)^{3/10}\ N \quad , \tag{42}$$

where μ is the atom-perturber reduced mass in units of u, N the perturber density, and C_6 the interaction constant. C_6 may be roughly estimated as follows: $C_6 = C_k - C_i$, with $C_{i\ (k)} = (9.8 \times 10^{10})\ (\alpha_d\ R^2_{i\ (k)}\ \alpha_d$ in cm^3, R^2 in a_0^2). Mean atomic polarizability $\alpha_d \approx$ $(6.7 \times 10^{-25})\ (3I_H/4E^*;)^2$ cm^3, where I_H is the ionization energy of hydrogen and E^*; the energy of the first excited level of the perturber atom. $R^2_{i\ (k)} \approx 2.5\ [I_H/(I-E_{i\ (k)})]^2$, where I is the ionization energy of the radiator. Van der Waals broadened lines are red shifted by about one-third the size of the FWHM.

For the $1s2p\ ^1P^o_1$ - $1s3d\ ^1D_2$ transition in He I, and with He as perturber: $\lambda = 6678.15$ Å; $I = 198\ 311$ cm^{-1}; $E^* = E_i = 171\ 135$ cm^{-1}; $E_k = 186\ 105$ cm^{-1}; $\mu = 2$. At $T = 15\ 000$ K and $N = 1 \times 10^{18}$ cm^{-3}: $\Delta\lambda^W_{1/2} = 0.044$ Å.

Stark broadening due to charged perturbers, i.e., ions and electrons, usually dominates resonance and van der Waals broadening in discharges and plasmas. The FWHM for hydrogen lines is

$$\Delta\lambda^{S,H}_{1/2} = (2.50 \times 10^{-9})\ \alpha_{1/2}\ N_e^{2/3} \quad , \tag{43}$$

where N_e is the electron density. The half-width parameter $\alpha_{1/2}$ for the Hβ line at 4861 Å, widely used for plasma diagnostics, is tabulated in the table below for some typical temperatures and electron densities [30]. This reference also contains $\alpha_{1/2}$ parameters for other hydrogen lines, as well as Stark width and shift data for numerous lines of other elements, i.e., neutral atoms and singly charged ions (in the latter, Stark widths and shifts depend linearly on N_e). Other tabulations of complete hydrogen Stark profiles exist.

Values of Stark-broadening parameter $\alpha_{1/2}$ for the Hβ line of hydrogen (4861 Å) for various temperatures and electron densities.

T(K)	N_e (cm^{-3})			
	10^{15}	10^{16}	10^{17}	10^{18}
5 000	0.0787	0.0808	0.0765	...
10 000	0.0803	0.0840	0.0851	0.0781
20 000	0.0815	0.0860	0.0902	0.0896
30 000	0.0814	0.0860	0.0919	0.0946

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Published April 26 - May 2, 2000

Dr. Randell Mills suspects outsiders tampered with his patent application.
(photo: Robin Holland)

THE EMPIRE STRIKES BACK
BY ERIK BAARD
Alternative-Energy Scientist Fights to Save Patent

D r. Randell Mills's physics and chemistry laboratories may have strangely united three forces that were presumed distinct: the U.S. Patent and Trademark office, the Department of State, and the American Physical Society. Unfortunately for Mills, they appear to have united against him.

This is a case for patent-dependent Nasdaq hopefuls and their investors to watch.

Mills, a Harvard-trained medical doctor and founder of the New Jersey-based technology start-up BlackLight Power Inc., was awarded a U.S. patent February 15 covering his claim to producing energy by shrinking the electron orbit of hydrogen below what most quantum theorists have thought possible for a century. He calls the smaller hydrogen atom a "hydrino" and theorizes it could lead to a nearly limitless supply of clean, cheap power [see "Quantum Leap" and "Doctor Molecool"].

The news outraged Mills's fiercest critic, Dr. Robert Park, an APS spokesman and avid debunker based in Washington, D.C. Park mocked the patent decision in the press and in his What's New column at aps.org. The column comes with a disclaimer that states, "Opinions are the author's and are not necessarily shared by the APS, but they should be."

Within days, the patent office pulled back a related chemistry patent for further review just before issuance, citing comments by Park and others—none of whom has tested Mills's devices or materials—in mainstream press reports that Mills must be either wildly mistaken or a fraud. That patent application, number 09/009,294, was so near issuance that it slipped out in the PTO's weekly *Gazette* of allowances as Patent No. 6,030,601.

Mills says Park may have more than the safeguarding of science at heart. "Park's group is lobbying the government to give them billions of dollars for 'big science' projects that BlackLight's success would make obsolete. He's a

competitor," says Mills, who is privately funded. "I know it's not completely analogous, but going to him would be like the patent office going to Bill Gates and asking, 'Do you think Apple's new operating platform will work?' "

With the novel hydrino chemistry, Mills says he's developed and had outside testing of the prototype for what could be a vastly superior class of batteries. He also claims to have developed compounds for plastic magnetic storage media and rustproof coatings, also with many independent lab verifications.

Mills's lawyers won an agreement from the patent office not to act on the chemistry application until June while the U.S. District Court examines the case. Meanwhile, Mills continues to take a beating at the agency, which took his artificial-intelligence patent application away from an examiner who'd been reviewing it for over a year and placed it in the hands of another, who quickly rejected it. The office also rejected his patent application for a hydrino power plant. Mills says he'll contest both decisions.

The 69-year-old Park and 42-year-old Mills have never met, but Park has blasted Mills since he proposed his theory nine years ago. In March, Mills's lawyers warned Park and three other scientists to refrain from calling him a fraud, even if they continue to denounce his theories. "Scientific debate is sacred—no one wants to silence that," Mills says. "But when you try to incriminate a business, you've crossed the line. Still, in a way I'm glad about this. It forces the issue. Now we'll have to put up or shut up, and they'll have to confront the data or fold." Mills says he's going to back up his filings with the patent office with more than 40 reports and publications, and he may request that the National Institute of Science and Technology test his prototype technologies.

Park says he doesn't know where Mills is on what he calls "the road from foolishness to fraud," because "the human capacity for self-deception should never be underestimated." Of course, he offers, even with a crank theory "there's room for serendipity, but I wouldn't bet on it."

Threats to the hydrino patents could jeopardize Morgan Stanley Dean Witter's plans to underwrite BlackLight's estimated billion dollar initial public offering. And some of BlackLight's backers say they're offended when portrayed as dupes or coconspirators.

"If I wanted to gamble, I'd fly to Vegas," says Rick Barry, whose Eastbourne Capital Management and its principals invested $5 million in BlackLight after what he describes as "detailed" due dilligence by him and PacifiCorp. "I don't think the risk [with Mills] is science fraud. It's can he engineer a device and can he protect his intellectual property? I thought we were safe on the latter until this started to unfold."

Along with PacifiCorp, electric utility Conectiv has invested in BlackLight. Tyco International inherited a sliver stake in the company through its purchase of Amp Incorporated, a leading producer of electrical connectors. Individual backers are among the Who's Who of the business establishment. They include a former chairman of Morgan Stanley and a former president of PaineWebber. Board members include Dr. Shelby Brewer, a former top Department of Energy nuclear official, and Aris Melissaratos, former director of Westinghouse's Science and Technology Center.

So while BlackLight doesn't have the resources of the entire physics establishment, it has more pull than most start-ups. Its travails at the patent office have even attracted attention on Capitol Hill.

Responding to evidence presented by allies of BlackLight, senators Ron Wyden of Oregon and Max Cleland of Georgia say they want to know if an

American Physical Society colleague of Park's at the State Department messed with Mills's application. One indication of outside influence noted by BlackLight attorney Jeffrey Melcher was that the patent office says it had lost the file when it ruled on the chemistry application. "That's not normal for an agency," says a Senate source. "If there's no record, how can you make a decision?"

The source says there may have been some improper contact by outside influences with patent officials, and points to Park's APS associate Dr. Peter Zimmerman, chief arms-control scientist at the State Department. Zimmerman boasted in an abstract for an upcoming APS lecture that "my own Department and the Patent Office have fought back with success" against "pseudoscientists," but didn't name his targets. His abstract railed against, among other things, inventors of "hydrinos."

A State Department official, who declined to be identified, said Zimmerman's abstract, which has since been removed, was missing a disclaimer explaining that he was speaking only as a private citizen. The official added that department employees are not allowed to use their titles outside of their official capacities. "The topic is totally outside our purview and mandate," the official said. "His views did not reflect those of the State Department."

Park and Zimmerman have certainly affected patent-office affairs before. Patent Examiner Tom Valone was invited by the State Department to organize an April 1999 Conference on Free Energy to explore alternatives to fossil fuels, many of which were controversial. Zimmerman told an APS gathering that Park asked him to put a stop to it.

"The week before I was to start [at the State Department] Bob [Park] sends me an e-mail, in which he tells me in some detail about the Conference on Free Energy under the sponsorship of the Secretary of State's Open Forum. It says, 'Pete, if you can't get that killed, what's the point of having you at the State Department?' "

Listen to Speech Clips
(clips provided by *Infinite Energy* magazine)

The conference was evicted from the State Department auditorium and then from the Department of Commerce.

Park says he then called "an investigative reporter" who writes for *Science*, suggesting he look into the patent office. The reporter, APS physicist David Voss, wrote a scathing article in the magazine's May 21 1999 issue describing Valone's personal interest in novel theories, while acknowledging he never approved patents with questionable backing. Nonetheless, Valone says the report contributed to his dismissal.

Mills has his own battles to wage. "We intend to fight this all the way to the Supreme Court," he says, "and enlist whatever resources it takes in Congress and industry to rightfully win this."
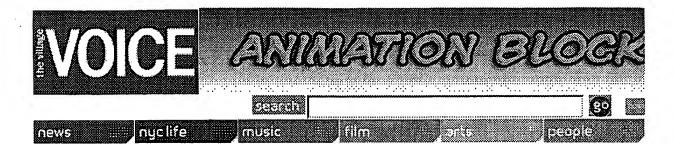
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Quantum Leap

**Dr. Randell Mills says he can change the face
of physics. The Scientfic Establishment thinks
he's nuts.**

by Erik Baard
December 22 - 28, 1999

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Times are tough on Robert Mills
Sr.'s 91-acre grain farm in Chester
County, Pennsylvania. "This year is
very, very bad," he confides. "I'm
glad the kids got out."

His eldest, Robert Jr., has a water
well drilling business, his daughter
Raeleen is a massage therapist.
And his younger son, Randell,
recently bought a 53,000-square-
foot space satellite manufacturing
plant near Princeton, New Jersey,
from Lockheed Martin. He then
stocked it with millions of dollars of
high-tech gear. Here the younger
Mills plans to overturn quantum
theory as it's been understood for
decades.

Dr. Randell Mills at his Princeton, New
Jersey, laboratory
photo: Robin Holland

Randell Mills, a Harvard-trained medical doctor who also studied
biotechnology and electric engineering at the Massachusetts Institute of
Technology, says he's found the Holy Grail of physics: a unified theory of
everything. A central part of Mills's theory explains the basis of the
traditional, and paradoxical, "duality" concept of the electron as both a
particle and a wave with a model where electrons are charges that travel
as two-dimensional disks and wrap around nuclei like fluctuating soap
bubbles. He calls them "orbitspheres."

Mills says that with this new understanding he's produced clean and
limitless energy and an entirely new class of materials and plasma that
will reshape every industry in the coming decade. Mills also claims
breakthroughs in artificial intelligence, cosmology, medicine, and perhaps
even a form of gravitational jujitsu.

"I've made the electron real," the 42-year-old Mills says. "It's a revolution

very fitting to the 21st century, in a chain of revolutions man has had with fire, steel, fossil fuels, and Maxwell's description of electromagnetism. This is grandiose stuff, and when I say it, it delivers a beating from critics. But on the other hand it's fun."

Though the topics he broaches could be coming from a B-movie mad scientist, Mills's cadences are more often like those of a motivational speaker. He moves his six-foot-five frame with athletic ease and drives a BMW sports car. He and his wife, an investment banker, have two young sons and another child due in March.

His company, BlackLight Power Inc., formed in 1991, expects to receive in January patents on the energy and chemicals, which Mills says derive from "shrinking" the hydrogen atom's orbitsphere. BlackLight Power, with a research staff of 25, will submit its findings to premier scholarly journals by that time, he adds.

Despite howls from the scientific establishment that Mills is a relic of the "cold fusion" trend quashed a decade ago, BlackLight Power Inc. has raised more than $25 million from about 150 investors. While that's hardly a huge sum in this Internet-crazed era, it's coming from serious money and energy people. Prominent among them are multibillion-dollar electric utilities PacifiCorp, based in Oregon, and Conectiv, which serves Mid-Atlantic states. RS Funds, Eastbourne Capital Management, and executives retired from the top echelon of Morgan Stanley have also put in millions. With Mills holding on to controlling shares, BlackLight Power now is turning away private investors.

"I'm impressed with how Randy's gone about this," a retired Morgan Stanley executive says, "with experiments to test the theory at every step. And the potential payoff is almost unimaginable."

Conectiv senior vice president David Blake concurs: "We're past the scientific verification stage. The talk now is about commercial applications," perhaps within seven years, he says. Blake sits on the BlackLight Power board of directors.

Morgan Stanley Dean Witter & Co. is considering a public offering of BlackLight Power stock in 2000. The investment bank says that the two chief needs that will trigger an IPO are a licensing agreement with a "household name company" and more substantial academic validation of its technologies. BlackLight Power is in discussions with DaimlerChrysler, and three major corporations are already examining materials it has produced, say Mills and company executives.

In the next year, Mills promises, the revolution will be "hydrinoized."

In one of BlackLight Power's cavernous laboratories sits the prototype energy-and chemical-producing cell that is the heart of Mills's ambitions. Mills explains that in this contraption, resembling a souped-up home furnace, water is electrically then catalytically broken down into atoms of oxygen and hydrogen. Potassium atoms are introduced as a gas into the very low-pressure hydrogen gas waiting inside the cell. Under specific conditions, the potassium acts as a catalyst to collapse hydrogen's electron orbit. The energy once used to maintain the higher orbit is released as ultra-violet light, Mills says.

The heat from that process can build pressure to turn a turbine for a generator or an engine, BlackLight Power notes in a marketing plan. The smaller hydrogen atoms, called "hydrinos," remaining in the cell can then react with other elements placed there to form novel compounds with amazing properties, Mills claims. "This will change how most everyday things in the 21st century are made and used," he says. For example:

EHydrinos combined with inorganic elements produce conductive, magnetic plastics that would revolutionize circuitry and aerospace engineering, and shrink and speed up semiconductors.

EHydrinos combined with highly oxygenated matter would form the basis of batteries the size of a briefcase to drive your car 1000 miles at highway speeds on a single charge, without gasoline.

EOne type of hydrino combined with an acid would produce incredibly powerful explosives or rocket propellants.

EHydrino and metal compounds make for super-strong coatings, some of which could make ships rustproof, dramatically reducing crew complements.

There are "millions and millions of possible combinations" in the commercial world, Mills says, revealing himself as a practical, earthy businessman.

These qualities emerged in his teens when he made good money raising corn and hay on land he leased. He had no college plans, and skipped so many high school classes his diploma was in doubt. But when he sliced up his hand and arm in an accident falling into a glass door, the five hours of surgery rattled his sense of immortality.

"At that point," Mills recalls, "I figured if I'm going to die eventually, I'd like to at least know why. I wanted to know how it works. All of it, from the human brain to the universe."

He used profits from the farm to cover the tuition at Franklin & Marshall College in Lancaster, Pennsylvania, where he graduated first in his class. After that he breezed through medical school at Harvard University, while simultaneously taking science courses at the Massachusetts Institute of Technology.

The son of a farmer, and a farmer himself, turned out to be an academic superstar.

"It's the American story," says Dr. Robert Park of the American Physical Society. "But he's still wrong."

Park has concluded that the hydrino theory is wrong in his upcoming book, Voodoo Science: The Road From Foolishness to Fraud. Park is not alone is being rankled by hydrinos. The hydrogen atom is the simplest, most common, and most tested element. It's nearly universally agreed that a free-floating hydrogen atom is in what's called "the ground state"—you can't bring its electron closer into its nucleus. Telling physicists that they've got that wrong is like telling mothers across America that they've

misunderstood apple pie. It's that fundamental.

"If you could fuck around with the hydrogen atom, you could fuck around with the energy process in the sun. You could fuck around with life itself," claims Dr. Phillip Anderson, a Nobel laureate in physics at Princeton University. "Everything we know about everything would be a bunch of nonsense. That's why I'm so sure that it's a fraud."

Dr. Michio Kaku, a theoretical physicist based at City University of New York, adds that "the only law that this business with Mills is proving is that a fool and his money are easily parted." Kaku is a cofounder of "string"-field theory, which posits that all matter and energy are actually manifestations of vibrations occurring in 11 dimensions. String-field theory, considered radical when it was introduced, is now pretty much the only game in town for mainstream physicists seeking a grand unified theory.

BlackLight Power boosters scoff that they've seen no practical application of quantum theory since the atomic bomb and nuclear power, and say they have little time for theorists who call Mills a charlatan while teaching that the fundamental mechanics of cause and effect are subverted at the subatomic level. Mills's camp responds: Fraud? Let's talk about fraud. Quantumists have us living in myriad dimensions filled with "probability waves" and unobservable "virtual particles" that flit in and out of existence, and they say we may one day slip through wormholes in space to visit other universes or go back in time.

Kaku insists that such seemingly far-out visions direct us toward truths we can't yet see, whereas Mills, Kaku contends, is promoting something already shown to be impossible.

"I'll have demonstrated an entirely new form of energy production by the end of 2000," Mills responds. "If Dr. Kaku has escaped our universe through a wormhole by then, I'll send my first $1000 in profits to his new address."

And there's the nub, Mills's critics also charge. They're talking the scientific method, and he's already spending his profits.

"The history of science in America since money became so easily available to people making outrageous claims has gotten very complicated," says Dr. Robert Cava, a materials science expert at Princeton. "Scientists are constantly in competition and constantly under extreme scrutiny. Don't think it's a picnic. So when someone comes along and makes a big splash without going through the rigors of peer review, it makes us think that the guy has no business doing it."

Dr. Richard Wilson, a research professor of physics at Harvard who says he's still skeptical of Mills's theory after a visit to BlackLight Power's labs, says the culture clash between scientists and captains of industry is natural.

"In my experience in science," Wilson says, "no one's more gullible than the wildcatter in the oil industry. But they're both gullible and successful. Sometimes they happen to be right. They take chances. That's their game, but that's not what scientists usually do."

The booming stock market of the 1990s has loosed a torrent of cash in all industries, but wallets have been especially fat in the U.S. utility industry in the last couple of years since that $215 billion business began deregulating. States have pushed electric companies to sell power plants to new competitors at open auctions. The result: In addition to coal, they have cash to burn.

A chunk of that money has been earmarked for new energy alternatives to fossil fuels, reflecting mounting concerns about global warming that have coalesced with long-standing unease with North American, European, and East Asian dependency on unstable regions for oil supplies. In the political climate of the U.S. at least, nuclear power isn't an option.

Of course popular "green," or environmentally sensitive, energy sources like solar, wind, and small-scale hydroelectric power don't require revisions to science textbooks. Mills says BlackLight Power is moving first on the energy and materials front, even though he's more credentialed in medicine, mostly because there are fewer regulatory hassles.

Out back behind Mills's laboratories is what is essentially a 150-ton thermos that he says will be the core of his first power plant. Lockheed Martin used it to test satellite components for the cold vacuum of space. But shielding on its one-inch-thick skin could also hold in heat produced by banks of Mills's cells placed inside. Old power plants could be retrofitted with BlackLight Power reactors, which would produce no emissions or hazardous waste, Mills says.

Conectiv has the right to license the BlackLight power process to make electricity, David Blake says. Another board member is Shelby Brewer, former chairman and CEO of ABB Combustion Engineering, a leading maker of power plants and nuclear fuel. Brewer has a Ph.D. in nuclear engineering from MIT, and was a top nuclear official in the Department of Energy during the Reagan administration.

"I think he has something here worth taking forward commercially," says Brewer, who now has his own energy company. But even those who say they've gotten positive results from testing Mills's energy cells stop short of endorsing his theory.

Dr. Johannes Conrads, former director of the Institute for Low Temperature Plasma Physics at Ernst Moritz Arndt University in Greifswald, Germany, told a gathering of the American Chemical Society in October that he was able to produce "remarkably high energy" from a Mills cell. But Conrads said he thought the energy could be coming from an effect within dense regions of plasma produced through the BlackLight Power process.

Dr. John A. Spitznagel, chief scientist for Siemens Westinghouse Power Corp.'s science and technology center in Pittsburgh, says that several years ago he too was intrigued by energy he was getting from a Mills cell, but that it wasn't enough to pursue at that time. But he remains "in a sort of monitoring mode" should Mills return with further verifications and the more refined approach that BlackLight Power claims to have developed.

Despite many qualms about the hydrino theory, Spitznagel says that he believes Mills "speaks with honesty and conviction." Spitznagel notes that one reason Mills didn't pursue further energy work with Siemens Westinghouse was that BlackLight Power focused for a time on the novel compounds Mills was producing.

National Aeronautics and Space Administration scientists were also encouraged that the Mills cell seemed to be producing energy, but they couldn't rule out alternatives to the hydrino effect as the cause, says Dr. Janis Niedra of NASA's Glenn Research Center. Niedra broke with many other scientists in a letter following an interview, writing that while Mills's theory butts up against popular interpretations of quantum mechanics, "in fact, however, quantum mechanics may permit such [hydrino electron] levels."

If Mills is right, Niedra wrote, "not only would such transitions give off hard UV light, but also the probability of room temperature nuclear fusion of the shrunken hydrogen, or deuterium, atoms would be greatly increased. The continuation of such processes to higher atomic numbers would of course emulate the power generation of a star! Considering the potential value of a new energy source, it seems worthwhile to restudy the Mills [proto]type cell in configurations allowing an accurate account for recombination and water loss."

When two nuclei are forced to fuse under high temperatures and pressures, copious amounts of energy are released. It's the power behind the hydrogen bomb and the sun. But two generations of physicists have failed to master nuclear fusion despite the billions of government dollars sunk into it.

Attempts to achieve cold fusion, the same result without adding great heat and pressure, have been given the cold shoulder since 1989 when two chemists in Salt Lake City cried "Eureka!" in the media but then couldn't provide others with a systematic way of reproducing their claims. The backlash was so virulent that government and university research grant writers run from anything that smacks of cold fusion.

Mills is adamant that his work is unrelated to cold fusion, even as diehards in the field attempt to claim him as their own. Dr. Charles Haldeman says he also was tripped up in cold-fusion phobia after he produced excess energy from several variations of a Mills cell while a senior staff member at the Air Force's MIT-managed Lincoln Laboratory in Lexington, Massachusetts.

"I got pretty good gain compared to the power I was putting in. The effect wasn't as large as Mills was getting, but it was in the direction that was predicted," Haldeman says. Because the results were smaller than he'd hoped, which he now says may have been due to contaminated materials,

he wasn't in a position to fight management when funding was stopped.

"They said, 'There must be some other error that you're not including,' but I couldn't figure out what it might be and neither could they," Haldeman says. "This area is clearly not well understood. There's clearly incontrovertible evidence that there's something going on in the work of Mills and others that certainly deserves further study. It's a tragedy that the politics of cold fusion has prevented science from taking its course."

Michael Jacox, assistant director of Texas A&M's Commercial Space Center for Engineering and a nuclear engineer, says he felt compelled to study the Mills cell in relative secrecy when he was a research scientist for the Department of Energy. While at the Idaho National Engineering and Environmental Laboratory, Jacox says he read about the Mills cell and decided in 1991 to perform independent experiments along with electrochemical experts on staff in battery development.

"We actually purchased a total of three large electrolytic cells and conducted very controlled experiments," Jacox says. "We followed the protocols Randy suggested and followed his technique and we got the same results he had," Jacox says. "We were encouraged but we determined that what we had was probably not sufficient to break a news release, especially with [cold fusion] going sour so soon before."

The team began more thorough testing, Jacox says, including side-by-side comparisons of catalyzed cells and control cells, when his bosses suddenly balked.

"In the middle of that process there was a management decision that said we should pull the plug on the whole project and not disclose that we had been involved in the project at all," Jacox says. The team decided to instead investigate hydrino compounds in "almost a clandestine operation."

"We probably have hundreds of different projects going on at all times, and this isn't one I was aware was going on," says John Walsh, a spokesman for the Idaho lab.

Researchers at other well-known government labs also say they are afraid to speak on record about their interest in Mills's work. One said that he plans to visit BlackLight Power on his vacation time. Jacox says his team found in the materials "an anomaly that we could not explain with conventional theory but that we could explain with Randy Mills's theory. That does not necessarily validate the Mills theory, but gosh."

Jacox continued to be frustrated by the proscription against testing Mills cells, "so I left the lab in large measure because of that."

Applied scientists have a rigorous standard in their work that is sometimes referred to as the Kmart Test. In other words, can the research at hand lead to an off-the-shelf product? By this criterion, the materials wing of BlackLight Power has great potential. Energy is a messy thing to measure, but as Mills says, "the good thing about materials is that they exist, or

they don't. There's no argument."

BlackLight Power's marketing people say they expect far more profits from compounds than from the energy released by hydrinos. The energy portion could even be seen as a mere spin-off of the chemical manufacturing that should simply be used, rather than wasted. Even the unpersuaded Professor Wilson of Harvard offers, "Maybe he hasn't found the gold of a grand unified theory, but there could be some silver there" in the hydrino compounds.

Tests at Lehigh University are interesting, confirms Dr. Alfred Miller, a senior research scientist there who has tested BlackLight Power's compounds. Miller probed the energy levels of the atoms by bombarding them with X rays and measuring the energy of the electrons leaving the atoms—a technique called X-ray photoelectron spectroscopy. "I try and exhaust all possibilities and there really aren't an enormous number of conventional explanations" for what he found.

Miller emphasizes that he didn't want his tests being interpreted as unequivocally confirming the hydrino theory, but "over the years I haven't really come across too many things that haven't been explainable. At least if you thought about it long enough and hard enough."

Because Mills has produced freely available physical materials and has been "incredibly more open in getting people to confirm what his hypothesis predicts . . . this is not the equivalent of cold fusion," Miller says. "He's serious and honest. . . . He may well have ventured upon something."

Ricerca Inc.'s lab east of Cleveland was similarly flummoxed by what it found when studying BlackLight Power's materials. "They were inorganic compounds that have organic properties. That is unusual," says Dr. Yong-Xi Li, manager of Ricerca's advanced mass spectrometry lab. "We totally don't know what's going on. The reason is that I've never seen before these kinds of properties in all my career. Probably we have to do more work."

The BlackLight Power research has excited the U.S. Navy, but the company isn't entirely thrilled with that. "It's kind of like letting a lion loose in the building," Mills remarks. "You have to remember that their goal is to find better ways of killing. But there are worse militaries [than that of the U.S.] out there."

Board members have another concern about getting too deeply involved with the armed forces. Some say they fear that the military could "black out" the project, making it a national security secret. That would deprive the company of other commercial prospects.

The issue came up at a BlackLight Power board meeting, according to sources. Executives at the meeting urged Mills to refer to energetic materials as potential propellants, and not explosives, even though a rocket is just a controlled explosion. One source says Mills bridled at the inherent intellectual dishonesty in the euphemism.

"That would be as if I pointed a duck gun at you and said not to worry, because it only kills ducks," Mills reportedly said.

BlackLight Power and researchers at the weapons division of the Naval Air Warfare Center at China Lake, California, confirm that they are heading toward a research and development pact that would allow the navy to produce energy and materials from hydrinos and to develop applications of the new compounds. A spokeswoman for the Indian Head Division of the Naval Surface Warfare Center in Maryland says in ane-mail letter that after a meeting with Mills "there was considerable interest in the reported properties of the new hydrogen-containing compounds, and in obtaining samples for independent analysis and evaluation."

BlackLight Power's newest board member is retired vice admiral Michael P. Kalleres, who commanded the U.S. fleet in the Atlantic during the Gulf War and the North Atlantic Treaty Organization's Striking Fleet. He's also a consultant for the Defense Science Board and the Naval Studies Board of the National Academy of Science.

"I feel very confident in what [Mills] has created," Kalleres says. He adds that he has no investment in BlackLight Power and takes no salary from the company, although he anticipates an option to invest later. After observing the company's practices for years, he believes that it's produced things of which the military should make use.

Ships with hydrino material cladding would likely be stealthy and rustproof, Kalleres says. Eliminating rust could radically reduce crews on some ships, savings millions of dollars.

It's not just BlackLight Power's work in bombs, rockets, and rusty ships that has the military's attention. Mills has stacks of proprietary research on artificial intelligence. In what he calls Brain Child Systems, Mills has done the math for a reasoning machine with consciousness. To advance the project, Mills may soon enter into a collaboration with the Institute for Simulation and Training at the University of Central Florida, which does the bulk of its work for the military.

But Mills wasn't thinking of the military when he began his work in artificial intelligence. Mills has a lifelong dream of making spaceships to travel at near light speed, and he says that only a mind with the switching rates of a computer could pilot them. A human brain, which Mills disdains as "wet processing," would fly into a rock before its owner could blink.

If spaceships are to hit such speeds, NASA scientists agree that rockets are a dead end. Mills says the answer may again lie in the electron, which according to his theory might be made to respond negatively to gravity. He quickly emphasizes that this part of his work awaits experimentation, and he has kept quiet about it so far because he's quite aware of how his critics will ridicule it. Mills is uncharacteristically coy in referring to the antigravity machine as a "relativity device."

There was a moment when it seemed NASA engineers might look into Mills's antigravity theory. Luke Setzer, a mechanical engineer at the Kennedy Space Center in Florida requested permission to investigate the idea's potential. Setzer says as a mechanical engineer, he's more intuitively comfortable with Mills's deterministic view of the universe.

Engineers, he says, "are used to classical physics. Mills applies classical physics to the subatomic level." Setzer was encouraged by his two managers to pursue the work, but after NASA physicists objected, "I dropped the whole thing." Without their nod, there would be no funding. "One of them kept referring to 'fictional energy' rather than theoretical energy" after glancing at Mills's self-published thousand-page tome, *The Grand Unified Theory of Classical Quantum Mechanics* (1995), Setzer says. "That kind of language tells me they're already shutting their minds to possibilities."

Setzer also plans to visit BlackLight Power's labs on his vacation time. "I think he's a real Renaissance man," Setzer says. "And even if reality is different than his theory, it could still be another source of energy. The Mills theory may accurately predict previously inexplicable phenomena. That doesn't mean that he's right, but string theory seems less well defined than Mills's theory yet is more accepted than Mills's."

Marc Millis, who is leading NASA's Breakthrough Propulsion Physics Project, says that a major reason for not pursuing BlackLight Power projects is that tight budgets dictate that administrators approach ideas with a triage mind-set. "If someone else has the funds to get behind an idea, why should we redouble that?" he asks. "We have to use our resources for things that look promising and we know we'll have to do for ourselves."

The craft Mills imagines would be made of hydrino compounds and powered by hydrino engines and batteries. There would be pods containing intersecting helium and electron beams under a negatively charged plate. The electrons in the beam would be deformed in such a way that they would oppose gravity and push up against that electric field of the negative plate, Mills theorizes. Anything attached to the plate would also experience lift.

Every part of the craft, except the electrons, is still subject to gravity. "Once you've got it up, what would you use to travel horizontally?" Mills asks.

Thrusters?

Mills gently waves that solution away. "Too inelegant. Try a flywheel to play off angular momentum," he suggests, "and the craft itself would act as an airfoil."

Yes, that would be a flying saucer.

The universe his flying saucers would explore was not made in six days nor in a big bang, Mills says.

"The Big Bang is not a theory. It's a fact," Dr. Michio Kaku claimed at a recent lecture at the New York Public Library.

Mills argues that the universe is forever oscillating between matter and energy over thousand-billion-year cycles, expanding and contracting between finite set points. In fact, he says, the universe doesn't get much smaller than it is now.

His theory predicted in clear language two recent astronomical discoveries—one, the universe is expanding at an accelerating rate, and, two, there are stars that measure as older than the expansion of the universe itself.

He also says hydrinos explain several mysteries about the sun and are the unidentified "dark matter" that astrophysicists say makes up most of the universe. Mills sees the conversion of matter into energy as the engine of universal expansion. Einstein and others showed that a mass creates a dimple in space-time. As that mass burns itself out, throwing off energy, that dimple formed by gravity is smoothed, causing the universe to expand, Mills explains.

"The sun is turning matter into energy every second; that forces the universe to expand," Mills says. "Even, in the tiniest way, the chemical reactions in your body are pushing the universe out."

Eventually all of this action expends itself until the universe becomes a giant cloud of photons that begin to gather into themselves to create matter again.

"You're existing, maintaining your internal order as a life-form, at the expense of your surroundings. The more you do to keep yourself as you are, in that order, a being as opposed to inanimate matter, the universe is going to decay at a faster rate. Eventually your borrowed time runs out and then it's dust to dust," Mills says. "It's sad, but that unfortunately is how it is.

"It's a beautiful thing that we can exist the way that we do for the time that we do and people should appreciate it," he says.

Does it all start over again in exactly the same way, as some religions teach? Is there a God?

Mills is at first curt. "That can't be experimentally tested, so I won't speculate on it." But then he adds, "There are some questions science will never answer. That's where you have faith."

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Eureka?
Hydrino Theorist Gets Nod From NASA-Funded Investigation

by Erik Baard
December 6th, 2002 11:30 PM

WRITE TO US
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Randell Mills has pledged for a decade to spark a **revolution in physics** that will not only overturn much of the atomic science that been taught and rewarded since the early 20th century, but will also provide a source of clean and nearly limitless energy.

But his centerpiece theory—that one could harness such fuel by shrinking hydrogen atoms into so-called hydrinos—has never fired so much as a single light bulb for public confirmation. A casual observer would say that instead of changing the world, Mills has built a cult following and a company, **BlackLight Power** Inc., embroiled in lawsuits over lost patents and continually broadsided by critics in the scientific media. More quietly, however, some scientists are taking notice. The National Aeronautic and Space Administration dispatched mechanical engineering professor **Anthony Marchese** from Rowan University to BlackLight's labs in Cranbury, NJ, to investigate whether energy plasmas—hot, charged gases— produced by Mills might be harnessed for a new generation of rockets. Marchese **reported** back to his sponsor on Monday, the NASA Institute for Advanced Concepts, that indeed the plasma was so far unexplainably energetic.

"Something interesting, something unexplained is happening in those cells," Marchese told the *Voice*. For now, the energy appears to be just hydrogen atoms bouncing around randomly at extremely high speeds—to create thrust for a rocket, in his next phase of research, Marchese will have to find a way to direct them out of the nozzle. Still, his findings indicate that Mills may indeed be on to something. Meanwhile, Mills's research is getting another kind of validation, from a perhaps even more surprising quarter—the stringent academic press. A paper by Mills and BlackLight research staff on their plasma work is set to appear next week in the prestigious Journal of Applied Physics. "I've been avoiding the media because we've gotten hit pretty hard there," Mills says. "But we've been publishing academic papers at a remarkably steady rate. I love this work—we're not slowing down."

The editor of the **Journal of Applied Physics**, James Viccaro, defends the decision to give space to the maverick. "His paper underwent formal review and was accepted for publication based on review. The findings are quite interesting and the reviewers found them relevant to the field," Viccaro says. "I'm actually kind of interested to see what happens now, when the news hits."

Marchese says he remains agnostic about the existence of hydrinos, and Mills's paper doesn't mention them, either. Rather, the report simply notes that these high-energy plasmas are created only with the company's catalysts. Hydrino theory has been blasted as a crackpot idea, and a member of the **Hydrino Study Group** once wrote a comprehensive refutation of Mills' ideas in **Skeptic** Magazine. Astrophysicist Aaron Barth cited "errors in Mills— work which render the hydrino idea meaningless as a physical theory." He also pointed out that Mills has given sloppy attribution for lengthy passages of standard physics background in endnotes rather than footnotes.

Marchese says BlackLight's experiments wouldn't be difficult for a serious lab to reproduce. "I have not been one to explore anything beyond the fringes of science until this point in my career, and I may never do it again," says Marchese, 35, who got a $75,000 grant from **NIAC** to conduct the initial six-month investigation. The funding was mocked by Robert Park of the American Physical Society, best known as a debunker of what he terms "voodoo science," as soon as it was announced. NIAC

and Marchese proceeded anyway.

"I was there quite a bit and really looked around, kicked the tires, talked at length with their engineers, observed their experiments, and did my own," Marchese says. "I'm really pretty confident as I'm ever going to be that there's no fudging going on. For me to not continue with this study would be unethical to the scientific community. The only reason not to pursue this would be because of being afraid of being bullied."

Viccaro of Applied Physics knows the feeling. He says publication of the paper shouldn't be read as an embrace of hydrino theory. "I guess we are sticking our necks out, but I can't just reject it because I have some preconditioned thinking about it," Viccaro says. "He made it through fair and square—he answered all the questions."

The debate over Mills's work has long since left the realm of pure science. Mills has won patents only to have them stripped away after public and private objections from people like Robert Park. Park even went so far as to falsely charge in Forbes magazine that Mills was claiming a cancer cure from hydrinos. In 1988, Mills published a paper on cancer therapy in the journal Nature that relied on conventional physics— he hadn't conceived of the hydrino yet.

Still, it's been over a decade since Mills first proposed the hydrino theory and the public doesn't have so much as a flashlight based on it. As Skeptic publisher Michael Shermer says, "The proof is in the hydrino pudding. The question is, when are you going to have desktop hydrino pudding?"

Outsiders, even sympathetic ones, complain that the company has shifted its proving grounds from heat measurements to electricity from plasmas, to materials and now a dense liquid hydrogen. Mills describes the seemingly meandering work as a "whole laundry list of stuff, questions to answer as milestones to reach before commercialization. We've basically rammed things down over the past year and a half. We've gone through about 150 catalysts and 50 variant cells."

Investors have been patient. Having garnered about $30 million from prominent backers since the founding of his company, Mills says he's close to wrapping up the fundraising phase . "We're almost completely done with the core science. We're getting to the point where we're not going to need a lot of money," he explains. "Our focus is on scaling up for commercial applications." One likely early product is a simple space heater, he says. If true, that would finally put the revolution squarely in the corner of the room.

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Spatially and temporally resolved electron density measurements in streamers in dielectric liquids

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Peter Bårmann[†], Stefan Kröll[†] and Anders Sunesson[‡]
[†] Department of Physics, Lund Institute of Technology, PO Box 118, S-221
00 Lund, Sweden
[‡] ABB Corporate Research, Department H, S-721 78 Västerås, Sweden

Abstract. *Spatially and temporally resolved spectroscopic measurements of
light emitted from positive streamers in transformer oil are presented.
Analyses of the measurements performed with a DC needle - plane gap yield
electron densities and indications of the atomic excitation temperatures in the
streamers. The hydrogen emission reveals an electron density below
10^{16} cm^{-3} during the main part of the streamer propagation time (80 -
90%). Later the light is also characterized by emission from a high-density
plasma with electron densities in the range $10^{18}-10^{19}$ cm^{-3}. The electron
density during this time increases approximately linearly with distance from
the initiation point and a density factor of four higher has been measured at
the streamer tip than at the root. Measurements with high spectral resolution
detect both high and low electron densities simultaneously. A tentative model
of the interior of the streamer plasma, spatially resolved, is presented.*

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BlackLight Power - do they have something significant?
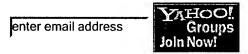
Randy Mills of BLP (Blacklight Power) has made some staggering claims of alternative physics and new forms of energy. He has an MD from Harvard and a number of scientists working for him. This web page is part of an effort to find out, "are his claims a chimera or significant". Some have said he has used lawyers to suppress dissent. I'm looking for more information and people willing to investigate some of BLP's "evidence". I have found that he really has the degrees claimed and someone else said tests on compounds looked interesting.

I'm a skeptic with a long running interest in the long history of false free energy claims. I've made a close investigation of Dennis Lee and Joe Newman. I'd rather that there be near free energy. It would solve many environmental and political problems. I offer a $10,000 prize for proof of this sort of thing. So far, I've seen no evidence for free energy, but I have been victimized by powerful forces resorting to dirty tricks to attempt to silence the voice of skepticism. There is a paperback pop-science book by John Gribbin that explains in laymens terms why you can't shrink hydrogen atoms. The name of the book is: *"The search for superstrings, symmetry and the theory of everything"*

you can find his discussion of why atoms are the size they are on pages 53-55.

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Replication of Mills Light Water Calorimetry Experiment - Introduction - 22NOV00
Weird scienceThe Village Voice: story on Mills . . and Another story on Mills' medical claims
The Order of the Tortoise - an effort to look for proof Tortoise Members
hydrino linksHydrino Study Group
Merriman-Mallove Pact
CETI Cold Fusion Experiment - a failed attempt to replicate their claims
Deja.com: Re: Mills sics lawyers on physicists
http://members.tripod.com/Hydrino/Essays/Due-Diligence.htm
what about CETI? - this includes a proposal to measure cells
Failed attempt to replicate excess energy

Mill's use of lawyers to intimidate open discussion
Peter Zimerman's review of Mill's theory

Media stories on BLP and Mills:

Mention of the BLP controversy from the Dallas Morning News
 Academics Question The Science Behind BlackLight Power, Inc.: The Harvard Crimson Online
Fill 'Er Up: With Plasma? Wild Science: Entrepreneur Takes On Quantum Theory Harvard
M.D.Challenges Big Bang Theory
LA Times story

Note In section 23.153-154 of Mills theory, he totally confuses units of time and distance.
It has also been pointed out that large areas of Mills theory appear to have been lifted from
another source with out proper attribution.

the following is a dialog which occurred on the free energy email list.

>I got my copy from Peter Jansson, P.P., P.E. who did the test and
>write up for his masters thesis from Rowan University in New Jesey.
>The title is Hydrocatalysis: A New Energy Paradigm for the 21st
>Century. Peter is a straight shooter and I have no reason to
>believe that he would falsify or bias any of the tests he did. As
>I said, he left Atlantic Energy (now Conectiv) and is pursuing his
>doctorate at MIT and was planning on doing some work with Cambridge
>too.

Thank you very much for the info.

In a quick net search, I turned up the following:

    Title : Hydrocatalysis : a new energy paradigm for the 21st
        century / by Mark Jansson.
    Author : Jansson, Peter Mark.
    Call Number : Publisher : 1997.
    Subject Heading(s): Power resources.
            Heat engineering.
    Description : iv 73 leaves : charts ; 29 cm.
    Notes : Thesis (M.A.)--Rowan University, 1997. Includes
    bibliographical references.

I note that it's a Master of Arts (as opposed to Master of Science)
thesis. Any idea what department awarded the degree?

I also found:

    Similar results have been obtained in other laboratories,
    including in a test run by Peter Jansson, an engineer and
    manager of market development for Atlantic Energy Inc.
    Jansson, who conducted the test independently of his company,
    said Atlantic Energy was "strongly considering" what he called

a "strategic investment" in BlackLight Power.

(http://www.keelynet.com/energy/hydmills.htm)

Does the Jansson thesis cover this test?

I also found:

Betty Kennedy, a spokesperson for Connectiv, said the New Jersey
utility has in investment in BlackLight as "part of an R&D effort
to keep us in the forefront of technology." The investment was
made by Atlantic Electric, now a part of Connectiv, and was
evaluated by a researcher who is no longer on staff. Ms. Kennedy
said this was unusual. Atlantic Electric generally turned to
Safeguard Scientific, a Pennsylvania company, for help in
evaluating companies with emerging technologies. She does not
know why Safeguard was not consulted in this instance.

(http://www.pacpub.com/new/business/b012099.html)

Does anybody know if Peter Jansson has any financial connections
with Blacklight Power?

I'm becoming less and less interested in this thesis. Before I go
through the effort and expense of ordering it through Rowan
University, could you please quote the relevant section that
lead you to make the statement "the people doing the tests seem to
have found varying amounts of anomalous energy". i.e. what kind of
energy (heat? electrical?) and how was it measured? How large were
the input and output flows of energy? Does the author directly state
that he measured "anomalous energy"?

Thanks again.

Nasa report:

TITLE: **Replication of the Apparent Excess Heat Effect in a Light
Water-Potassium Carbonate-Nickel Electrolytic Cell**

Document ID: 19960016952 N (96N22559) File Series: NASA Technical Reports

Report Number: NASA-TM-107167 E-10118 NAS 1.15:107167

Sales Agency & Price: CASI Hardcopy A03 CASI Microfiche A01 - No Copyright

Authors: Niedra, Janis M. (NYMA, Inc.) Myers, Ira T. (NASA Lewis Research
Center) Fralick, Gustave C.   (NASA Lewis Research Center) Baldwin, Richard S. (NASA Lewis
Research Center)

Abstract:
    Replication of experiments claiming to demonstrate excess heat production in light
water-Ni-K2CO3 electrolytic cells was found to produce an apparent excess heat of
11 W maximum, for 60 W electrical power into the cell. Power gains range from 1.06 to 1.68. The cell
was operated at four different dc current levels plus one pulsed current run at 1 Hz, 10% duty cycle. The
28 liter cell used in these verification tests was on loan from a private corporation whose own tests with
similar cells are documented to produce 50 W steady excess heat for a continuous period exceeding
hundreds of days. The apparent excess heat can not be readily explained either in terms of nonlinearity
of the cell's thermal conductance at a low temperature differential or by thermoelectric heat pumping.
However, the present data do admit efficient recombination of
dissolved hydrogen-oxygen as an ordinary explanation. Calorimetry methods and heat balance
calculations for the verification tests are described. Considering the large magnitude of benefit if this
effect is found to be a genuine new energy source, a more thorough investigation of
evolved heat in the nickel-hydrogen system in both electrolytic and gaseous loading cells remains
warranted.

Major Subject Terms:
   TEMPERATURE EFFECTS LIGHT WATER CARBONATES ELECTROLYTIC CELLS
THERMOELECTRICITY ENERGY TECHNOLOGY

Minor Subject Terms:
   NICKEL SPACECRAFT POWER SUPPLIES THERMAL CONDUCTIVITY POTASSIUM
COMPOUNDS HEAT MEASUREMENT

Eric's attempt to directly contact people purported to support BLP's assertions:

I got through to **Alfred Miller** of Lehigh university. He knew of no one doing calorimetry
studies. He has done XPS studies on samples Mills gave him.   He's seen interesting
things that are not easily explained - but is very clear that it is still inconclusive. He
doesn't poo poo this stuff out of hand, but I gather that he is not convinced the laws of
physics must be rewritten either. I don't believe his skill areas overlap my own. So I can't
really conclude anything significant from his data. It doesn't support Mills - but it doesn't
prove him a fraud either.

Chuck Haldeman has worked for **Lincoln Labs** and spent 2 -3 years trying to get it up to
the power levels Mills said. He only got **5 watts excess power** - That's taking a known

power in from a power supply calibrated with HP equipment (some of the time they ran pulsed power in).
He says you have to subtract input power needed to electrolyze the light water. He calculates that power from the volume of gas produced. *(chance for error?)* He says others reviewed his work and found no trouble. He was most forth-coming. He's not convinced that Mill's theory is correct, but he does feel that there is proof of anomalous energy out. I for one do not know if there is a prosaic chemical explanation of what is happening. It sounded like he was very thorough about energy measurements and proper calibration. He was never convinced that he saw evidence for the shrunken hydrogen -- what he saw using *speed of sound, compressibility* and other tests appeared to be argon and another gas that he think leaked through teflon. His company decided to abandon searching for ways to make it work better. He did say it ran for weeks putting out consistent energy. It ends up being a 1.5 degree heat flux from their cell that tells them the energy levels. He says their ambient is consistent and that they calibrate the relationship between energy output and temperature gradient by running resister heating. Haldeman is an older guy who says he has been following what people call CF for some time. So far, this seems like the best evidence for excess heat - but unfortunately it is not set up so I can't take a trip down to see for myself.

David McMahon says "*Mills entire theory is based on an error. There is nothing to it, so I accept nothing about hydrinos. I accept nothing Mills says about quantum mechanics. Mills does not seem to understand quantum mechanics in the first place. There is no math or theory to think about regarding hydrinos because the entire concept is worth nothing as far as I can tell.*"

- the following appeared on the hydrino email list
A friend of mine who has read some of Mills papers has some questions I would like to throw out for discussion:

1. If this is all a classical problem across 45 orders of magnitude as he(Mills) claims, there seems to be a problem. Consider the problem of a macroscopic positive point source suspended within a negatively charged sphere. There is an equilibrium point with the point being in the center of the sphere, but the system is fantastically unstable. The slightest perturbation will cause the two to leave the equilibirum point and collide. Mills hammers Bohr for his postulates of the electron orbit, yet he seems to be postulating too. How can this point-shell configuration be stable?

2. If the orbisphere is a sphere, how do electrons leave nuclei? Do the nuclei rip through the sphere? How does the sphere repair itself? How long does it take to repair itself?

3. How thick is the orbisphere? If the orbisphere has constant mass, then as it resizes, the thickness changes and the rotation velocity changes. Eventually in his 1/n scheme, the orbisphere rotation speed will exceed c.

4. I see the word orbisphere a lot. I should see orbiellipsoid. Does he deny that electron clouds have elliptic shapes?

5. The pre-Bohr problem: As I read the Mills paper, he talked about 1/n orbit

levels. Why doesn't the electron cascade from 1/2 to 1/infinity and crash into the nucleus once it leaves the ground state? He spends time discussing why the electron can't go from the ground state to the 1/2 state, but he doesn't seem to explain the mechanism of subsequent transitions.

The following is offered from a Chemistry professor:

Dear Eric:

I put another hour into blacklightpower.com.

So far it seems that there are no papers in peer-reviwed journals on the website. The techical papers available seem to have no journal reference. The "papers" presented at ACS meetings are talks, not papers, and are not peer-reviewed.

Technically, there is not much I can follow, but they say in the first "technical paper" that conversion of a hydrogen atom (whose existence as a free species is doubtful, but is on a metal surface apparently)
to a hydride ion makes it smaller. The sizes on my big laboratory chart say the opposite. There was no obvious source of electron to make the negative hydride ion.

A statement is made in the first technical "paper" that "Alkali nitrates are extraordinarily volatile, and can be distilled at 350-500 deg. C. This sounded wrong, so I looked up all the ones I could find in the CRC Handbook. Lithium nitrate decomposes at 600? C, sodium nitrate at 380?, potassium nitrate at 400? and cesium nitrate at over 400?.

So two blunders were found, making the whole business suspect.

Yours, Joel

Other posts to the Hydrino email list of interest:

From: DMc74965@aol.com
Subject: Re: Re: Orbitspheres PowerPoint Presentation

In a message dated 5/28/00 9:51:55 AM Mountain Daylight Time, tlollerpe@peoplepc.com writes:

<< 1 Deterministic BC.
2 Orbitsphere vs point particle
3 no "infamous" uncertainty principle
DR Mills theory is DETERMINISTIC. >>

Deterministic BC? This claim by Mills has never made sense to me. The probability interpretation is not a boundary condition. Members of the group who have taken partial differential equations should know that. The so-called fourth boundary condition, that the wave function goes to zero as r goes to infinity, is not a "boundary condition" either. That is a result of the wave function being square-integrable. If you want to know what boundary

conditions are, see Griffiths derivation of the infinite square well
potential on page 24 of his Introduction to quantum mechanics book.
Incidently, the infinite square well, while somewhat artificial, is a very
instructive example that allows one to understand the hydrogen atom more
fully, including why energy is discrete. Now what about the "infamous"
uncertainty principle? The uncertainty principle is not only "infamous" is
has been shown correct in tens of thousands of experiments and has not once
been proven wrong. The uncertainty principle can also be derived from first
principles in mathematics, both from fourier analysis and from linear
algebra. It should not be surprising that it comes from fourier analysis,
since free particles can be thought of as wave packets. It is also not
surprising that it can be derived from linear algebra, since wave functions
form a complex vector space. For a proper description of what the uncertainty
principle means (instead of what is found in the latest Shrodinger Cat book)
I would reference interested readers to Griffiths pages 17-19 and pages
108-111.

Some notes/questions about Mills paper "The Hydrogen Atom Revisited":

Page 8: Equations 44-45: Mills incorrectly asserts that the Schrodinger
equation corresponds to the case where the constant c_1 fails to vanish and
leads to infinite solutions. This is incorrect, as anyone who has had a
quantum mechanics class with the derivation of the hydrogen atom can attest.
The constant c_1 is set to zero. This is demonstrated in Griffiths on page134,
equation 4.5.7.

Mills then goes on to describe the solution for an ionized electron and
states that it would be infinite, cannot be normalized. He also states the
angular momentum of the free electron would be infinite. This is a good
example that shows Mills does not understand QM. For one, the solutions for
the free electron are taken to be a superposition of seperable solutions to
the schrodinger equation, which DOES produce a normalizable solution for a
free particle, which is called a wave packet. The superposition is obtained
by integrating over k.

I also find Mills discussion of a free electron in this context bizaare. For
one, who would use the schrodinger equation in the context of the coulomb
potential to obtain the solutions for a free particle? Free particle
solutions are obtained by using schroginders equation with the potential set
to zero, and then integrating over k as I just described. Now what about the
infinite angular momentum? Angular momentum with respect to what? The
nucleus? If the electron is "free" and it is basically out to r at infinity,
what meaning does this have?

On Page 10, Mills states that the Sch. equation is not lorentz invariant and
violates SR. Well, no kidding. The Sch. equation is used in non-relativistic
situations. You don't trot out SR unless called for. And there is a wave
equation that obeys SR and can be used in relativistic situations, its called

the Klein-Gordan equation.

On Page 2, equation 1, Mills lists the Rydberg equation. There is a sign error. Either nf and ni should be reversed, or R should have a minus sign. As listed, it would give negative frequencies. Also, why does Mills list En with the ground state energy out to 3 decimal places? Perhaps I am picking nits here, but that is kind of strange to write it like that, it is written as -13.6.

On page 3 he refers to a "Rutherford orbit" and says that Rutherford proposed a planetary model of the atom to explain the spectral lines of hydrogen. I have never heard the term "Rutherford orbit". Rutherford proposed that the charge and mass of the atom were concentrated in the nucleus to explain scattering of alpha particles, as far as I know this concept was not proposed by Rutherford to explain spectral lines (I checked in Modern Physics by Kenneth Krane to make sure my memory was not failing). It says that it was Bohr who proposed the planetary model to explain the hydrogen spectrum.

I find the digression to attempt to explain Bohr's theory with standard orbital mechanics on pages 4 & 5 strange, non-standard and bizarre.

Overall, I find this paper is sloppily written and I could see why it would be turned down by a professional physics journal.

and

From: ab1097@xxxxxxxx
Subject: Helpful information

Hello all,

I have examined Mills's work, as posted on the BLP web site, in some detail. Since I haven't been to BLP I can't claim any knowledge of what's going on in his labs. However, I can say with total confidence that the theoretical aspects of Mills's work are utter rubbish. The "theory" of hydrinos is completely full of mathematical mistakes, from start to finish. As a work of theoretical physics, it's totally meaningless, and it's so badly flawed that there really is no way to "repair" it.

For those of you who complain that the theory is often dismissed out of hand by professional scientists who do not give it due consideration, here's a bit of explanation for why the theory is so totally incorrect.

1. Mills starts with a standard scalar wave equation. This can't possibly be a valid equation for the electron in a hydrogen atom. For starters, the wave equation doesn't incorporate the electromagnetic force. So it's inconceivable that the solutions to

this equation could represent bound states of an atom which is held together by the electromagnetic force. (By contrast, the Schrodinger equation for a hydrogen atom does include the electromagnetic force.)

2. Also, the wave equation doesn't contain Planck's constant. Since we know that the electron's energy levels depend on this physical constant, it has to appear somewhere in the basic equation. (It does appear in the Schrodinger equation, of course.) I noticed that somewhere on the BLP web site Mills refers to his wave equation as a "Schrodinger-type" equation. This is completely misleading. He's starting with an equation which can't possibly have bound-state solutions.

3. How, then, does Mills get his "orbitspheres" to appear to follow the known energy levels of the hydrogen atom? Simple. He solves the equation incorrectly. His use of a delta function to solve the radial component of the wave equation is a bad joke. It's horribly wrong. The correct solutions are given by spherical Bessel functions. There is NO way to solve the wave equation with a delta function in radius, period. This is really basic, textbook stuff on differential equations. The so-called "solutions" that Mills gives do not actually solve the wave equation that he uses.

4. The point of all this is: If you start with the wave equation that Mills uses, and you solve it correctly (no matter what boundary condition you use), you will NEVER get solutions which look like bound states in a hydrogen atom. The claim that Mills's theory can correctly reproduce the known energy levels of hydrogen is completely without merit. There is no way to get the energy levels of hydrogen as solutions to an equation that does not include the electronic charge or Planck's constant. And it is TOTALLY incorrect to say that delta functions are a solution to the radial component of the wave equation. It's impossible for a delta function to be a solution to a differential equation like this, because the derivative of a delta function is not a meaningful quantity.

This is just the tip of the iceberg in terms of the gross mathematical and logical errors in Mills's work. I won't go on to list more of these, but I hope I've made the point that the starting point of the theory is so horribly flawed that nothing that follows from it could possibly be correct.

Thus, after careful consideration of the evidence, it's easy to conclude that there simply is no hydrino theory. The so-called "theory", as Mills proposes it, is just meaningless. Nobody with any understanding of quantum mechanics or differential equations could conceivably make such errors.

This isn't a theory that is even worthy of being tested by experiment. The "conclusions" and "predictions" of the theory are mathematically invalid, and they are not even mathematically consistent with the wave equation that is the starting point of Mills's theory. To say that the hydrino theory "predicts" anything at all would be completely untrue. I'd also like to point out that there's no truth to the statement that Mills's theory "challenges" the big bang, unless you consider a bunch of math mistakes to be a credible scientific challenge.

On the subject of peer review: Any referee for a reputable physics journal would catch these mistakes in a matter of minutes. It's not just a matter of scientists disagreeing with Mills's predictions or conclusions. It's that the math leading up to those predictions makes no sense, so the predictions are meaningless. If you are wondering why the "scientific establishment" doesn't take Mills seriously, it's because his work demonstrates a very dismal grasp of basic concepts of physics and math.

Bottom line: there is no mathematically consistent theory which predicts the existence of the hydrino. Mills's theory does not correctly predict anything whatsoever. There is no theoretical reason to believe that there is any such thing as a hydrino.

The following is another anonymous reaction to Mills' theory:

Eric,
　　　I have a Ph.D. in physics and I have went through the mathematical and theoretical derivations of
Mills in the book he published. In summary his results are incorrect. This is what he does.

　　　1) He starts out with the 3-D shroedinger equation to make things look respectable.

　　　2) Then he solves the z, theta, portions by separation of variables the usual way to make it look even more
　　　　　believable.

　　　3) Then a miracle happens and he assumes that he can solve the radial, r, portion by assuming that r is continues and not quantized.

　　　4) He uses this solution to rewrite all of his Quasi Quantum Mechanics and obtain all of his wacky results.

　　　In summary, Mills got a hold of some undergraduate quantum mechanics books and rederived everything assuming that
the radial part of the equation is continuous and not quantized. His results are BS.

PS (As usually the guy who gave me the Mills book to show me some "new physics" was some old misled engineer.)

Skeptic Magazine, Vol. 8 no 4 just came out with a nice 5 page article called "Bigger Than Fire - A Scientific Examination of Randell Mills' "Hydrino" Theory" by Aaron J. Barth.

It gives a standard overview of Mills and BLP that everyone on this list would be fairly well familiar with.

The article moves on to the mainstream Bohr & Schrodinger models. From there it discusses Mills' theory. Among the criticisms are "The wave equation that Mills uses doesn't contain any terms which describe this electromagnetic force, and it doesn't have "bound state " solutions which could potentially represent an electron physically attached to an atom." and "It's as though Mills were claiming that the waves should just stand still forever at a fixed distance from the spot where the pebble hit the water, rather than expanding away and traveling across the pond. The mathematical expression Mills gives for the charge-density function of the electron aren't solutions to any equation of motion at all.". He also accuses Mills of "artificially grafting the Bohr model onto his theory in a way that is mathematically nonsensical.". Barth slices up Mills' astrophysical evidence by pointing out that Mills harvests spectrometer band information from noise levels. He goes on to say that "The hydrino theory contains so many other severe flaws in its logic, mathematics, and physical interpretation that it would be impossible to list all of them here." Barth does say one nice thing: "It's possible that he has stumbled on some interesting new chemical process; ultimately peer review and market forces will decide whether any of his laboratory work has useful applications."

Efforts by BLP to suppress free discussion of the theory:

the following reflects a conversation that was posted to the hydrino email list between a skeptic and one of Mill's lawyers. I personally feel it is wrong to use lawyers to interfere with free discussion

--- this section is unfortunately down due to request by the original author ----

1

Emission in the Deep Vacuum Ultraviolet from an Incandescently Driven Plasma in a Potassium Carbonate Cell

H. Conrads*, R. Mills**, Th. Wrubel***

*   Wolfshovener Strasse 195, 52428 Jülich, Germany
** Black Light Power, Inc., 493 Old Trenton Rd., Cranbury, N.J. 08512, USA
*** Institute for Experimental Physics V, Ruhr University, 44780 Bochum, Germany

Abstract

Electromagnetic radiation in both the visible and vacuum ultraviolet (VUV) spectral ranges was emitted from an incandescently driven plasma in a potassium carbonate cell after the potassium carbonate coated on a titanium mesh was heated to above 750°C in a hydrogen atmosphere. The pressure was between 0.1 and 1 mbar, and the hydrogen was dissociated by a hot tungsten wire. Bright visible light filled the annulus between the coaxial tungsten heater and the titanium mesh. This grid was at a floating potential. The emission of the H_α and H_β transitions as well as the L_α and L_β transitions were recorded and analyzed. In the latter spectral range, the spectra show rotational-vibrational transitions of molecular hydrogen which belong to the Werner-band-system of molecular hydrogen. The plasma generated in the incandescently driven cell has phenomenological similarities to that of low pressure electrical driven discharges such as striations of the plasma or the appearance of unipolar arcs ending on metal surfaces. However, the plasma seemed to be far from thermal equilibrium and dependent on the chemistry of atomic hydrogen with potassium. Details of the chemistry powering a novel VUV-light source could not be revealed within the frame of this contribution.

I. Introduction

Table top sources emitting radiation in the deep ultraviolet spectral range are gaining more and more interest in photochemistry due to the increased functionalization of surfaces, particularly in combination with lithographic processes [1]. The range and complexity of applications are wide and range from simple sterilization of large surfaces to sophisticated nano-patterning in production processes of microelectronics and biotechnology [2]. Well known sources such as electric sparks [3], capillary discharges [4], pseudosparks, hollow cathode discharges [5], laser sparks, and barrier discharges [6], to name a few, are suited for
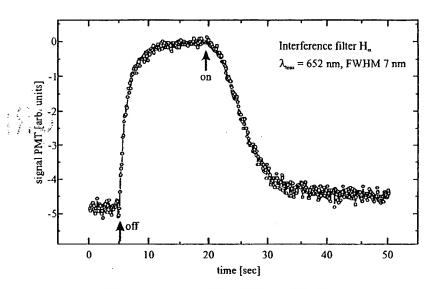
Figure 1: Emission of the cell as a function of time, while the heater current was turned of and on.

such photochemical work and are selected and developed further according to the specifications of the particular application.

Previously reported VUV emission of incandescently driven potassium carbonate cells in hydrogen [7] seemed to depend more on the chemistry of the potassium with hydrogen— with sodium carbonate no VUV emission was observed—and on the temperature of components in the cell than on a particular voltage or current applied to the cell. Figure 1 shows the decay and return of the H_α emission, which is indicative of an associated VUV emission, when the power was turned off and on in several ms. After turning off the heater power, the intensity dropped with a time constant of 2 seconds. With restoration of the original heater power, 10 seconds elapsed before the H_α emission reached its maximum again.

The following paper addresses the plasma and the VUV radiation generated in such a cell. The emission of the first two members of the Balmer and Lyman series were recorded with higher spectral resolution than before [7], and in contrast to earlier investigations, the tungsten wire was heated by external radiation as well as by ohmic heating.

II. Experimental set up

A. The Cell

Three different types of cells were used to investigate the formation of a low-voltage hydrogen plasma and the emitted radiation. One design, type I, was described previously [8]. In the second design, type II, the helical tungsten wire heater was replaced by two commercial 120 V halide bulbs connected in parallel. A tungsten wire was wrapped around the outside of the bulbs to serve as a hydrogen dissociator [9]. The tungsten wire in the type II cell as well as the titanium mesh were at a floating potential. All other components were the same as those of the type I cell. In the third design, type III, the thermal insulation of the quartz tube vacuum vessel of the type I cell was removed and replaced by an oven. An adjacent part of the tube had no insulation in order to allow for "side on" observation of the radiation. The rest of the quartz tube was covered by a brass tube that extended to the cap which provided the different supplies. The voltage supplied to the tungsten wire heater was increased step-wise from 20 V to 70 V. At 70 V, the color of the tungsten wire was similar to the one in the center of the oven.

For the Lyman series measurements, all of the cells were windowless and connected to a VUV spectrometer directly for "end-on" observation. The visible radiation was coupled to the spectrometer by glass fibers for "side-on" observation.

B. The Spectrometers

The light in the visible spectral range was analyzed by a grating spectrometer in Czerny-Turner mounting and recorded by a photomultiplier and oscilloscope as well as by an optical multichannel analyzer (OMA) system. A 1200 lines/mm grating blazed at 1000 nm was used. The light in the vacuum ultraviolet was analyzed by a scanning 1 meter grating spectrometer in Eagle mounting (McPherson, model 225) equipped with a grating of 1200 lines/mm blazed at 120 nm. The spectra were detected by a photomultiplier coated by a p-Terphenyl scintillator and recorded by an oscilloscope. The entrance and exit slits had a width of 50 μm. A pressure gradient was maintained between the cell and the pumped spectrometer.

III. Experimental Results

A. The Cell

The work was started with a type I cell. As soon as the temperature between the quartz wall and the thermal insulation of the cell exceeded 700°C, light was observed from the annulus between the helical tungsten heater and the titanium mesh coated with a thin film of potassium carbonate. The temperature outside of the quartz tube was increased to and held constant at 750°C. The bluish-white-colored emission that lasted for about one hour increased with temperature and was brighter than the glow of the tungsten heater. The experiment was repeated several times until the tungsten heater wire became brittle.

Rather than replace the tungsten wire, a series of experiments was performed next using the type II cell. With an electrically floating tungsten wire wrapped around the outside of the bulbs, the light in the annulus became bright after 10 minutes of heating and was observed to be different in color compared to the bright light emitted from the interior of the bulbs. The bluish-white light was easily observed by eye. The cell wall temperature was again 750°C. The light emission lasted about half an hour. Without the tungsten wire wrapped around the halide bulbs, no bluish-white light emission was observed.

No significant difference in the spectral emission or general performance could be determined between the type I and type II cells. Furthermore, the endurance of the bulbs in type II cell was not significantly better than that of the tungsten heater of the type I cell due to failure of the quartz walls of the bulbs under the resulting high-temperature conditions. The quartz of the bulbs developed plasticity with loss of mechanical stability above 1000°C. This behavior was not observed when the external tungsten wire was absent corresponding to the absence of the generation of the bluish-white light emission from the annulus. Since the operative temperature at the quartz wall of the type II cell was 750°C as well, it was concluded that an exothermic reaction was responsible for the generation of light in the annulus that also required the tungsten to be at a sufficiently high temperature and the presence of potassium carbonate on the titanium mesh.

Next a type III cell was studied. When a current was passed through the tungsten heater of a type III cell, a zone of about 5 – 10 windings was observed to have a significant lower temperature than the other windings as indicated by a difference in color. This cooler zone slowly migrated back and forth along the heater axis. Often several of these lower temperature
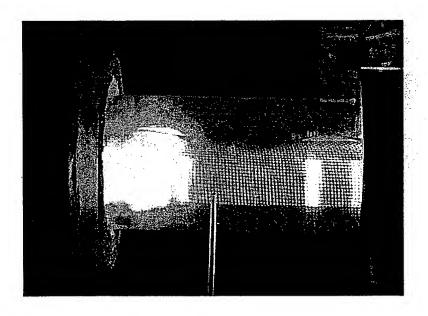
Figure 2: Photograph of the cell (type III). Bluish-white light can be seen at positions up to a few centimeters outside the oven (left) and the brass insulator.

zones were observed. A reasonable explanation for this phenomenon was that an electrical short formed across the zone of the darker windings due to a plasma created around the coil before the bluish emission in the annulus between the tungsten wire and the titanium grid could be visually observed. For the section of the heater that was observable, the voltage across the tungsten windings from one end of the cooler zone to the other was not more than 5 V. The emission of the tungsten wire and the associated voltage inside the insulating brass tube and the oven may have been different.

This segmentation of emission of the tungsten coil also remained active at a later stage when the light emission of the cell was fully developed as evident by the emission of the Balmer series of hydrogen. Then a greenish seam appeared around the dark zone directly pointing to an electrical short by a plasma. At this finally developed stage of the discharge, the bright zones of the tungsten wire shown in Figure 2 pointed to zones of higher axial electric fields. From the inhomogeneous light emission of the tungsten wire, it was concluded that an axial inhomogeneous field was generated in the annulus between the tungsten wire and the titanium mesh.

As shown in Figure 2, bluish light was emitted from the region between the titanium mesh and the quartz wall as well as from the annulus between the tungsten coil and the titanium mesh. A similar pattern was observed for the emission of white light. It was observed that a necessary

condition for this kind of emission was the existence of sufficient potassium carbonate on the titanium mesh, and the intensity of the bluish and white emission was related to the potassium carbonate concentration on the titanium mesh. In addition, it became evident that the temperature of the titanium mesh had to be sufficiently high to enable the emission. This was demonstrated by removing the oven and setting the tungsten coil at the rated voltage of 70 V for a time longer than that required to achieve strong emission. Only the red emission of the tungsten wire was observed. As soon as the oven was slipped over the quartz tube, the bluish and white emission started instantly.

Since the oven heating was sufficient to maintain the temperature of the titanium mesh sufficiently high for emission, the tungsten-coil heater power was reduced by decreasing its voltage. It was possible to sustain VUV light emission down to 20 V corresponding to about 0.2 V per winding and a field of about 0.1 V/cm. The light emission stopped with a voltage just below 20 V and returned at once when the voltage was restored to 20 V. When the voltage was set to zero for a while, the return of the light emission was delayed even when the voltage was quickly increased to 70 V. From these observations, it was concluded that the condition of a minimum tungsten-wire temperature was required in order to trigger the bluish and white light emission, when all of the other conditions were fulfilled. From the experiments with the light bulbs as heaters together with these findings, it was concluded that axial electric fields might be essential for the build up of the plasma and light emission, but an appropriately elevated temperature of the tungsten wire was necessary as well.

Radial plasma striations in the zones of bluish emission (see Figure 2) point to the existence of radial electric fields which might be generated due to chemical potentials in the vicinity of the titanium mesh or due to a Nernst potential because of a strong temperature gradient.

When the pressure in the quartz tube was raised to a couple of mbar, unipolar arcs developed on the titanium mesh. The dependence of this phenomenon on the voltage applied to the tungsten coil was similar to the case described above.

Striations of electric fields and their impact on electron properties in periodic states inside the plasma of a DC-glow-discharge have been analyzed in depth in references [10] and [11]. Since the observed space-resolved visible emission of the AC-driven cell is not very different from that in zones of DC glow discharges, it was concluded that the development of local electric field modulations and distinct non local electron properties may govern this kind of plasma as well. Dark zones in the annulus between tungsten coil and titanium mesh as well as outside the titanium mesh may have been zones of acceleration of free electrons. Electrons
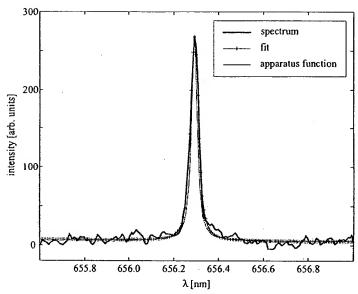
Figure 3: The emission of the H_α measured in second order together with it best fit and the apparatus function.

may have been accelerated axially and/or radially depending on the site in the cell. Inside the bright zones of the plasma the electrons may have lost a part of their energy due to interaction with heavy particles. A local pattern of the velocity distribution of the electrons in periodic states depends on partial pressures of the constituents and the local field distribution [10,11]. Both of these parameters could not be controlled during the reported experiments. It is therefore not too surprising, that the spectral emission such as that in the VUV varied between the different experimental runs as shown in Figures 4a and 4b. The plasma generated by the cell seems to be complex and requires further investigations. These issues are discussed in Sec. IV.

B. The Spectra

For the investigation in the visible spectral range, the wavelength was calibrated using a cold standard lamp that also served for the determination of the apparatus function which was fit by a Voigt profile of 0.96 pixels Gaussian and 3.89 pixels Lorentzian widths. In the first order, the width of the H_α transition ($\lambda = 656.28\ nm$) corresponds to that of the apparatus profile; whereas, in the second order, a broader and slightly asymmetric H_α profile was observed. Figure 3 shows the emission of the H_α transition measured in the second order with
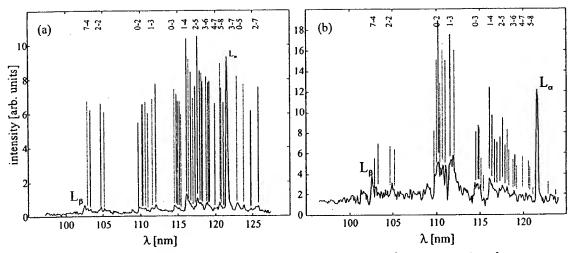
Figure 4: Examples of spectra of the L_α and L_β transitions showing rotational-vibrational transitions belonging to the Werner band system.

a reciprocal dispersion of 7.0 pm/channel together with a least squares fit. The calculated profile consists of three wavelength shifted Gaussian profiles according to the three fine structure transitions of H_α taking into account the intensity ratios given by [12]. The calculated profile is still asymmetric when it is convoluted with the measured apparatus function. Therefore, the asymmetry on the measured spectra can be attributed to the unresolved observation of the fine structure components. The fit gave a Gaussian width of (3.2 +/- 0.9) pixels corresponding to (22 +/- 0.06) pm. This served for an estimation of an upper limit of the ion temperature of $k_B T_e = (0.1 - 0.32) \, eV$.

The H_β transition was identified in the spectra measured in first order. It was not observed in second order because of its low intensity. The intensity ratio of the H_α and H_β transitions was determined to be 15 +/- 5 with a relatively high uncertainty due to the low intensity to noise ratio of the H_β transition. By assuming a Maxwell Boltzmann distribution of the level population, an electron temperature of $k_B T_e = (0.30 - 0.43) \, eV$ was deduced. Since the electron density of the present plasma was small, the assumption of a Maxwell distribution was somewhat questionable. Nevertheless, only a slightly higher temperature of $k_B T_e = (0.32 - 0.48) \, eV$ was found when a corona model was applied. In both cases, radiation transport was neglected in the calculations so that the temperature given represents an upper limit.
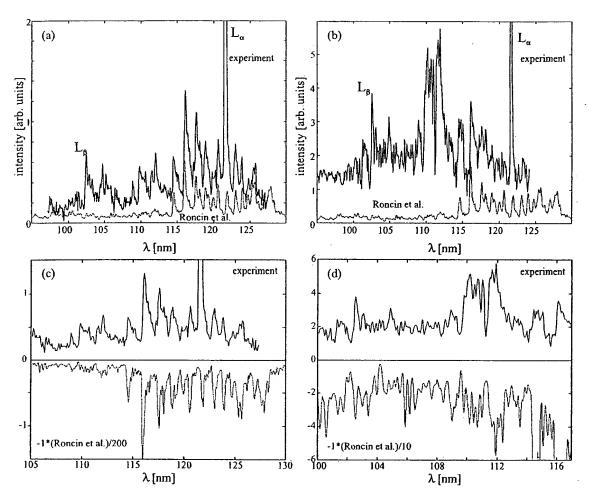
Figure 5: The measured spectra in comparison with a synthetic emission spectrum (intensity-scaled) of molecular hydrogen after /14/. a,c) and b,d) correspond to the experimental spectra in Figure 4a) and 4b), respectively.

Figure 4 shows two scanned spectra in the vacuum ultraviolet spectral range where the emission of the L_α and L_β can easily be seen. Strong emission of bands and lines were also observed in this wavelength region which will be discussed later. The intensity ratio of the L_α and L_β transitions was measured with a higher accuracy to be 16.5. For an optically thin plasma, the corresponding temperature of a Boltzmann level population is 62 eV. This excessive energy may indicate that this model is not applicable possibly because of the large distance of the energy levels. For these series transitions to the ground state, a corona model may be more suitable which gave an upper estimate of the electron temperature of

$k_B T_e = 1.6 \, eV$. Nevertheless, this temperature was also factors higher than the above estimated temperatures indicating that at least the emission of the L_α may have suffered from radiation transport.

In summary, the data indicate that the electron temperature of the present plasma was not higher than $k_B T_e = 0.5 \, eV$. On this basis, it was astonishing that the Lyman alpha and Lyman beta transitions appeared in the spectra since an excitation energy of 10.2 eV and 12.1 eV is required, respectively. The same holds for the Balmer series as well. The Lyman-α energy is a factor of about 20 above the measured thermal energy. The amount of electrons in the Maxwell tail that had enough energy to enhance the Lyman transition was 11 orders of magnitude lower than the total number of electrons.

Figure 5 shows the spectra of Figure 4 together with an emission spectrum of the Werner bands of the hydrogen molecules taken from reference [13]. The experimental spectra in this reference have a coincidence of 95% with theoretical results showing a high level of confidence. About 12,000 transitions were taken into account for the spectrum of Roncin et al. The relative intensities are presented as stated in reference [13], and the lines were convoluted with the measured apparatus profile. It is amazing to see the detailed similarity of the pattern of the energy levels between the experimental and the theoretical spectrum. Not only the vibrational but also numerous rotational transitions were identified in the spectrum of the cell. Similar to atomic emission, electronic transitions in low quantum numbers were preferred by the molecules in the plasma of the cell. However, the relative intensities of the spectrum in Figure 5(b) differed significantly from those of the spectrum of Roncin et al. in the range around 110 nm. This part of the spectrum belongs to a Werner band with $v' = 0$ and $v'' = 1$, respectively.

IV. Discussion

The emission of VUV radiation, and in particular, Lyman series and Werner band emission was observed from a low density plasma of quite moderate temperature similar to that in fluorescence tubes for general lighting. Such a plasma of an incandescently heated cell should not emit VUV radiation. The spectra showed that the plasma was far from thermal equilibrium. This was not too surprising because of the cell components, such as heater and titanium mesh etc., all may have contributed to a bimodal free-electron velocity distribution. But, the relevance of free electrons for the population of electronic levels is questionable

because of the preference for emission from a few specific electronic states of low quantum number. The same applies if a corona equilibrium was assumed.

Only blackbody radiation from the tungsten coil was observed at longer wavelengths. Based on the VUV emission, the plasma was predominately a hydrogen plasma. The ionization of atomic hydrogen requires 13.6 eV. In the cases where plasma was observed, no possible chemical reaction of the tungsten filament, the titanium screen, K_2CO_3, and low pressure hydrogen at a cell temperature of 750°C could be found which accounted for the generation and sustaining of the plasma. In fact, no known chemical reaction releases enough energy to form an atomic hydrogen plasma as treated in the following discussion.

The enthalpy of formation ΔH_p of potassium hydride is -14.13 $kcal/mole$ [14]. Thus, the formation of potassium hydride releases only 0.59 eV per atom. But, potassium hydride decomposes in this temperature range (288 to 415°C). Thus, it can not account for any emission of the hydrogen plasma.

The reduction of K_2CO_3 by hydrogen calculated from the heats of formation is very endothermic.

$$H_2 + K_2CO_3 \rightarrow 2K + H_2O + CO_2 \quad \Delta H = +122.08 \; kcal/mole \, H_2 \qquad (1)$$

The reaction absorbs 2.5 eV per hydrogen atom.

The most energetic reaction possible with oxygen is the reaction of hydrogen to form water which releases 1.48 eV per atom of hydrogen; whereas, the energy of Lyman emission is greater than 10.2 eV per atom.

The dissociation of molecular hydrogen on the filament produces atomic hydrogen which may recombine to release 4.45 eV. Since atomic hydrogen is neutral, no contribution from the electric field of the filament is possible. Thus, excitation with energies of 4.45 eV or less is possible by the transport of thermal energy from the filament due to hydrogen dissociation followed by recombination. But this reaction is not sufficiently energetic to support the observed VUV emission.

Chemical energy may have been transported from regions outside of the annular region where most of the emission was observed. Dense and cold plasmas may have been created close to surfaces such as the titanium mesh due to chemical reactions. In such non ideal plasmas with electron densities close to solid density and temperatures below 0.5 eV, the potential energy of the electrons becomes comparable to their kinetic energy, and energy levels of bound electrons in atoms such as hydrogen are altered such that excitation and ionization energies are lowered [15]. This also applies to other elements of the plasma such as potassium. The electronic energy levels of the different species are further distorted when interacting with

each other. The dissociation of molecules and ionization of both the molecules and atoms may become more probable with more species. However, the lowering of the ionization and excitation energies by the state of "non ideality" in dense plasmas is only about 1 eV even for potassium. Thus, the most energetic chemical source possible, dissociated atomic hydrogen, could not have provided more energy than the Frank-Condon energy of 4.45 eV during recombination. Thus, this mechanism can not explain the hydrogen plasma.

The measured electron temperature, 0.5 eV, is over an order of magnitude too low to account for the hydrogen plasma. The filament electric field as the energy source of the excitation is also eliminated. The emission occurred even when the electric field was set and measured to be zero. The results can not be explained by electric field acceleration of charged species since the estimated external field of the incandescent heater is extremely weak, about 1 V/cm. The electron mean free path at the operating pressure range of 0.1 to 1 mbar is about 0.1 cm corresponding to a mean energy from the acceleration of electrons in the field of about 1 V/cm of under 1 eV. Thus, electron collisional excitation of Lyman emission or hydrogen ionization by a so called 'run-away-situation' of the velocities of free electrons is not probable. However, the observed plasma striations outside the titanium mesh close to the mesh points may have been due to local radial electric fields in the plasma not yet identified, where charged particles were accelerated in the dark zones to energies high enough to excite bound electrons in the brighter zones [11].

Temperature dependent electric fields also arise due to the greater mobility of electrons compared to ions. The generated voltage U for a plasma with a similar ion and electron temperature T is given by

$$U = \frac{kT}{2e} \ln \frac{m_x}{m_e} \tag{2}$$

where m_x is the mass of the ion such as the potassium ion or a proton, m_e is the electron mass, and e is the electron charge. From Eq. (2), the maximum voltage corresponding to the potassium ion is of the order of 1 V.

Multi-collisional processes may be possible [16], but very dense, high-pressure plasmas are required, and given an electron energy of 0.5 eV, about 30 concerted electron collisions would be required within 10^{-8} s—a definite impossibility.

Resonant energy transfer is possible to give predominantly Lyman α and Lyman β emission. Kurunczi, Shah, and Becker [17,18] observed intense emission of Lyman α and Lyman β radiation at 121.6 nm and 102.5 nm, respectively, from microhollow cathode discharges in high-pressure Ne (740 Torr) with the addition of a small amount of hydrogen (up

to 3 Torr). With essentially no molecular emission observed, Kurunczi et al. attributed the anomalous Lyman α emission to the near-resonant energy transfer between the Ne_2^* excimer and H_2 which leads to formation of $H(n=2)$ atoms, and attributed the Lyman β emission to the near-resonant energy transfer between excited Ne^* atoms (or vibrationally excited neon excimer molecules) and H_2 which leads to formation of $H(n=3)$ atoms. However, the formation of this plasma resulting in Ne_2^* excimers and excited Ne^* atoms required a field of over $10^4 V/cm$; whereas, the field in the heated cells is on the order of 1 V/cm. Thus, this mechanism does not provide a source of energetic photons that may be resonantly transferred.

The titanium-mesh and the tungsten coil were present in all experiments. The emission was not observed with the cell alone, with hydrogen alone, or under identical conditions wherein Na_2CO_3 replaced K_2CO_3. When the power was interrupted, the emission decayed in about two seconds. Decay was recorded over a time greater than 10,000 times the typical duration of a discharge plasma afterglow [19]. This experiment showed, that plasma emission was occurring even though the voltage between the heater wires was set to and measured to be zero for a time duration which was surprisingly extended. Since the thermal decay time of the filament for dissociation of molecular hydrogen to atomic hydrogen was similar to the plasma afterglow duration of the investigated source which requires the presence of K_2CO_3 the emission was determined to be due to a reaction of K_2CO_3 with atomic hydrogen. The minimum temperature requirement of the tungsten wire for emission also demonstrated the emission reaction's dependence on atomic hydrogen.

A source of energy other than that provided by the electric field or known chemical reactions must be considered for explaining our experimental findings.

V. Conclusion

The generation of the Lyman and Balmer series and the Lyman Werner bands of molecular hydrogen requires energies significantly greater than 10 eV. The formation of a hydrogen plasma by the cell loaded with K_2CO_3 on titanium and operated in hydrogen required a minimum temperature. The heat from the filament and possibly the weak dipole field from the filament may sustain the hydrogen plasma; but, the latter is not essential because hydrogen lines were emitted during times when this voltage is set to zero. Furthermore, given the observations, free electrons can not excite these states. In the case that the free electrons should have been thermalized, their temperature was too low to contribute to excitation or ionization even from the tail of the velocity distribution. Longer range fields (of the order of mm) were

only about a 1 V/cm. In addition to electron collisional excitation, known chemical reactions, and resonant photon transfer, the lowering of the ionization and excitation energies by the state of "non ideality" in dense plasmas were also rejected as the source of ionization or excitation to form the hydrogen plasma.

The emission from a plasma was observed at low temperatures (e.g. $\approx 10^3\ K$) from atomic hydrogen and potassium. The release of energy from hydrogen was evidenced by the hydrogen Lyman and Balmer emission which identified the presence of a hydrogen plasma. The persistence of emission following the removal of all of the power to the cell indicates that an unknown chemical power source is present. The implication is that a new plasma and light source for the vacuum ultraviolet has been discovered.

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GRUNDLAGEN DER QUANTENMECHANIK

VON D. I. BLOCHINZEW

Professor an der Staatlichen Lomonossow-Universität, Moskau

6., durchgesehene und nach der 3. sowjetischen Ausgabe erweiterte Auflage

Dem Eigenwert m_l^2 (25, 21) entsprechen insgesamt $2l + 1$ Eigenfunktionen, die sich durch den Wert der Zahl m voneinander unterscheiden. Wir haben es also mit einem Fall von *Entartung* (siehe § 21) zu tun. Das Wesen dieser Entartung ist leicht zu erkennen, wenn man berücksichtigt, daß die Eigen-funktionen des Operators des Quadrats des Drehimpulses $\mathfrak{m}^2$ zugleich auch Eigenfunktionen des Operators m_z der Komponente des Drehimpulses in der z-Richtung sind. Die Gleichung für die Eigenfunktionen des Operators m_z ist ja

$$m_z \psi = m_z \psi. \qquad (25, 23)$$

Setzen wir m_z aus (25, 8'') ein, so erhalten wir

$$- i\hbar \frac{\partial \psi}{\partial \varphi} = m_z \psi.$$

Setzt man hier ψ_{lm} ein und berücksichtigt man, daß ψ_{lm} proportional $e^{im\varphi}$ ist, so findet man

$$- i\hbar \cdot im \psi_{lm} = m_z \psi_{lm},$$

d. h., die Gleichung (25, 23) wird durch die Funktion ψ_{lm} erfüllt, wobei die Eigenwerte des Operators m_z folgende sind:

$$m_z = \hbar m, \quad m = 0, \quad \pm 1, \quad \ldots, \quad \pm l. \qquad (25, 24)$$

Daraus folgt, daß bei gegebenem Quadrat des Drehimpulses m_l^2 (l ist auch gegeben) die Zustände ψ_{lm}, die sich durch den Index m voneinander unterscheiden, Zustände mit verschiedenen z-Komponenten des Drehimpulses dar-stellen.

Das von uns erhaltene Resultat zeigt, daß die möglichen Werte der abso-luten Größe des Drehimpulses und die möglichen Werte seiner Projektionen auf eine beliebige z-Achse (25, 24) gequantelt werden. In der Natur können keine anderen als die angeführten Werte realisiert werden. In Zuständen, bei denen $\mathfrak{m}^2$ und m_z bestimmte Werte annehmen, besitzen m_x und m_y keinen bestimmten Wert (mit Ausnahme des Falles $l = 0$, wo dann $\mathfrak{m}^2 = m_x = m_y = m_z = 0$), da die Funktionen (25, 22) keine Eigenfunktionen der Opera-toren m_x und m_y (25, 8), (25, 8') sind, wovon man sich unmittelbar über-zeugen kann. Das geht auch daraus hervor, daß m_x, m_y und m_z nicht ver-tauschbar sind.

Selbstverständlich verhalten sich die für m_x und m_y möglichen Werte genau-so wie die für m_z (25, 24), denn die z-Richtung ist durch nichts ausgezeichnet. Um sich von der Richtigkeit unserer Behauptung zu überzeugen, braucht man sich nur vorzustellen, daß die x-Achse oder y-Achse als Polarachse gewählt wurden. Wenn wir in diesem Falle m_x bzw. m_y messen würden, bekämen wir immer wieder einen der Werte von $\hbar m$ ($m = 0, \pm 1, \pm 2, \ldots, \pm l$), aber dabei entstünde ein neuer Zustand mit einem bestimmten Wert, angenommen z. B. m_x. Das wäre dann ein Zustand mit unbestimmten m_y und m_z, d. h.,

93

bewegung führen sowohl die klassische Theorie wie die Quantentheorie bei gleichen allgemeinen Voraussetzungen zu $-\dfrac{e}{2\mu c}$. Das Versuchsergebnis erschien daher rätselhaft. Nimmt man jedoch an, daß die Magnetisierung nicht durch die Bahnbewegung des Elektrons, sondern durch seinen Spin verursacht wird, dann muß das Verhältnis $\dfrac{|\mathfrak{M}|}{|\mathfrak{m}|}$ gleich $\dfrac{e}{\mu c}$ sein, wie es der Versuch auch ergibt. Diese Annahme ermöglichte nicht nur die Erklärung der Ergebnisse von EINSTEIN und DE HAAS, sondern ergab auch die Grundlagen für die moderne Theorie des Ferromagnetismus (siehe § 130).

Wir bemerken, daß gegenwärtig die Existenz des Elektronspins als Folge der von DIRAC entwickelten relativistischen Theorie des Elektrons betrachtet wird. Die Darlegung dieser Theorie überschreitet jedoch den Rahmen dieses Buches.[1]

§ 59. Der Operator des Elektronenspins

Wir wollen nun die mathematische Formulierung der Hypothese von UHLENBECK und GOUDSMIT entwickeln.

Übereinstimmend mit den allgemeinen Grundsätzen der Quantenmechanik stellen wir das mechanische Eigenmoment des Elektrons (wir werden der Kürze halber einfach Elektronenspin sagen) durch einen linearen selbstadjungierten Operator dar. Wir bezeichnen die Operatoren der Komponenten des Spins in Richtung der Koordinatenachsen mit s_x, s_y, s_z. Um die Form dieser Operatoren zu bestimmen, verlangen wir, daß sie den gleichen Vertauschungsregeln folgen wie die Komponenten m_x, m_y, m_z des Bahnmoments.[2] Setzen wir daher in (25, 5) $\mathfrak{s}$ statt $\mathfrak{m}$, so erhalten wir

$$\left.\begin{aligned} s_x s_y - s_y s_x &= i h s_z, \\ s_y s_z - s_z s_y &= i h s_x, \\ s_z s_x - s_x s_z &= i h s_y, \end{aligned}\right\} \qquad (59,1)$$

Die Komponente des Spins in einer beliebigen Richtung kann (nach der Ausgangshypothese) nur zwei Werte $\left(\pm\dfrac{h}{2}\right)$ annehmen. Daher müssen die Operatoren s_x s_y, s_z durch zweireihige Matrizen dargestellt werden, da

---

[1] Siehe DIRAC [16]. DIRAC hat gezeigt, daß aus der relativistischen Gleichung für die Elektronenbewegung sich von selbst ergibt, daß das Elektron ein magnetisches Moment (58, 2) und ein mechanisches Moment (58, 1) besitzen muß. Damit wird der Hypothese UHLENBECKS und GOUDSMITS die theoretische Grundlage gegeben.

[2] Mit Hilfe der Gruppentheorie kann man beweisen, daß die Regeln (59, 1) die einzig möglichen sind. Siehe z. B. [45].

228

eine zweireihige Matrix, auf Diagonalform gebracht, nur zwei Diagonal-
glieder hat und folglich nur zwei Eigenwerte besitzt. Nehmen wir an:

$$s_x = \frac{h}{2}\sigma_x, \quad s_y = \frac{h}{2}\sigma_y, \quad s_z = \frac{h}{2}\sigma_z, \tag{59,2}$$

so können wir sagen, die Operatoren σ_x, σ_y, σ_z (die Spinmatrizen) müssen
zweireihige Matrizen der Form

$$\sigma_x = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}, \quad \sigma_y = \begin{vmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{vmatrix}, \quad \sigma_z = \begin{vmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{vmatrix} \tag{59,3}$$

sein, die die Eigenwerte ± 1 besitzen. Setzen wir (59, 2) in (59, 1) ein und
kürzen durch $\dfrac{h^2}{4}$, so erhalten wir

$$\sigma_x\sigma_y - \sigma_y\sigma_x = 2i\sigma_z, \tag{59,4}$$

$$\sigma_y\sigma_z - \sigma_z\sigma_y = 2i\sigma_x, \tag{59,4'}$$

$$\sigma_z\sigma_x - \sigma_x\sigma_z = 2i\sigma_y. \tag{59,4''}$$

Mit Rücksicht darauf, daß die Eigenwerte von σ_x, σ_y, σ_z gleich ± 1 sind,
werden die Eigenwerte der Operatoren σ_x^2, σ_y^2, σ_z^2 gleich $+1$ sein. Folglich
müssen diese letzteren Matrizen in ihrer Eigendarstellung die Form

$$\sigma_x^2 = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix}, \quad \sigma_y^2 = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix}, \quad \sigma_z^2 = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \tag{59,5}$$

haben, d. h., sie sind gleich der Einheitsmatrix δ

$$\delta = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix}. \tag{59,6}$$

Die Einheitsmatrix bleibt Einheitsmatrix in jeder Darstellung (siehe § 40).
Daher haben die Matrizen σ_x^2, σ_y^2, σ_z^2 die Form (59,5) in jeder möglichen Dar-
stellung. Untersuchen wir jetzt die Kombination

$$2i(\sigma_x\sigma_y + \sigma_y\sigma_x) = 2i\sigma_x\sigma_y + \sigma_y 2i\sigma_x.$$

Auf Grund von (59, 4) kann sie auf die Form

$$(\sigma_y\sigma_z - \sigma_z\sigma_y)\sigma_y + \sigma_y(\sigma_y\sigma_z - \sigma_z\sigma_y) = \sigma_y\sigma_z\sigma_y - \sigma_z\sigma_y^2 + \sigma_y^2\sigma_z - \sigma_y\sigma_z\sigma_y$$
$$= \sigma_y^2\sigma_z - \sigma_z\sigma_y^2$$

gebracht werden. Wegen $\sigma_y^2 = \delta$ ist

$$\sigma_y^2\sigma_z = \sigma_z\sigma_y^2.$$

Folglich gilt

$$\sigma_x\sigma_y = -\sigma_y\sigma_x. \tag{59,7}$$

Man sagt, daß die Matrizen σ_x und σ_y *antivertauschbar* sind.

229

Kombinieren wir (59, 7) mit (59, 4) und wenden wir die zyklische Vertauschung von σ_x, σ_y, σ_z an, so finden wir

$$\left. \begin{array}{l} \sigma_x \sigma_y = -\sigma_y \sigma_x = i\sigma_z, \\ \sigma_y \sigma_z = -\sigma_z \sigma_y = i\sigma_x, \\ \sigma_z \sigma_x = -\sigma_x \sigma_z = i\sigma_y. \end{array} \right\} \qquad (59, 8)$$

Wir wollen jetzt die explizite Form der Matrizen σ_x, σ_y, σ_z finden. Nehmen wir an, daß die Matrix σ_z auf Diagonalform gebracht ist. Da ihre Eigenwerte gleich ± 1 sind, wird die Diagonalform von σ_z folgende sein:

$$\sigma_z = \begin{vmatrix} 1 & 0 \\ 0 & -1 \end{vmatrix}. \qquad (59, 9)$$

Es läßt sich zeigen, daß in der gleichen Darstellung die beiden Matrizen σ_x, σ_y die Form

$$\sigma_x = \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix}, \quad \sigma_y = \begin{vmatrix} 0 & -i \\ i & 0 \end{vmatrix} \qquad (59, 9')$$

haben.

Zum Beweis bilden wir die Produkte $\sigma_z \sigma_x$ und $\sigma_x \sigma_z$. Nach den Regeln der Matrizenmultiplikation (§ 40) haben wir

$$\sigma_z \sigma_x = \begin{vmatrix} 1 & 0 \\ 0 & -1 \end{vmatrix} \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} \\ -a_{21} & -a_{22} \end{vmatrix},$$

$$\sigma_x \sigma_z = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \begin{vmatrix} 1 & 0 \\ 0 & -1 \end{vmatrix} = \begin{vmatrix} a_{11} & -a_{12} \\ a_{21} & -a_{22} \end{vmatrix}.$$

Aus (59, 8) folgt

$$\begin{vmatrix} a_{11} & a_{12} \\ -a_{21} & -a_{22} \end{vmatrix} = - \begin{vmatrix} a_{11} & -a_{12} \\ a_{21} & -a_{22} \end{vmatrix} = \begin{vmatrix} -a_{11} & a_{12} \\ -a_{21} & a_{22} \end{vmatrix},$$

oder

$$a_{11} = -a_{11}, \quad a_{12} = a_{12}, \quad -a_{21} = -a_{21}, \quad -a_{22} = a_{22},$$

d. h.

$$a_{11} = 0, \qquad a_{22} = 0.$$

Daher hat die Matrix σ_x die Form

$$\sigma_x = \begin{vmatrix} 0 & a_{12} \\ a_{21} & 0 \end{vmatrix}. \qquad (59, 10)$$

Wir bilden jetzt

$$\sigma_x^2 = \begin{vmatrix} 0 & a_{12} \\ a_{21} & 0 \end{vmatrix} \begin{vmatrix} 0 & a_{12} \\ a_{21} & 0 \end{vmatrix} = \begin{vmatrix} a_{12} a_{21} & 0 \\ 0 & a_{12} a_{21} \end{vmatrix}.$$

Vergleichen wir das mit (59, 5), so finden wir, daß $a_{12} a_{21} = 1$. Die Matrix muß selbstadjungiert sein, d. h., $a_{12} = a_{21}^*$. Folglich ist $|a_{12}|^2 = 1$.

230

Daraus erhalten wir

$$\sigma_x = \begin{vmatrix} 0 & e^{i\alpha} \\ e^{-i\alpha} & 0 \end{vmatrix},\tag{59, 11}$$

worin α eine reelle Zahl ist.

Auf ähnliche Weise finden wir, daß

$$\sigma_y = \begin{vmatrix} 0 & e^{i\beta} \\ e^{-i\beta} & 0 \end{vmatrix}.\tag{59, 11'}$$

Multiplizieren wir jetzt σ_x mit σ_y und dann σ_y mit σ_x und verwerten (59, 8), so erhalten wir

$$\begin{vmatrix} e^{i(\alpha-\beta)} & 0 \\ 0 & e^{-i(\alpha-\beta)} \end{vmatrix} = - \begin{vmatrix} e^{-i(\alpha-\beta)} & 0 \\ 0 & e^{i(\alpha-\beta)} \end{vmatrix},$$

woraus folgt:

$$e^{i(\alpha-\beta)} = - e^{-i(\alpha-\beta)},$$

d. h., $\alpha - \beta = \dfrac{\pi}{2}$. Auf diese Weise sind alle Beziehungen bei beliebigem Wert von α erfüllt. Wir können also ohne jede Einschränkung $\alpha = 0$, $\beta = -\dfrac{\pi}{2}$ setzen. Setzen wir diese Werte in (59, 11) und (59, 11') ein, so erhalten wir (59, 9'). Nach (59, 2) erhalten wir aus (59, 9) und (59, 9') die Matrizen der Operatoren s_x, s_y, s_z in der Darstellung, in der s_z diagonal ist (s_z-Darstellung):

$$s_x = \begin{vmatrix} 0 & \dfrac{h}{2} \\ \dfrac{h}{2} & 0 \end{vmatrix}, \quad s_y = \begin{vmatrix} 0 & -i\dfrac{h}{2} \\ i\dfrac{h}{2} & 0 \end{vmatrix}, \quad s_z = \begin{vmatrix} \dfrac{h}{2} & 0 \\ 0 & -\dfrac{h}{2} \end{vmatrix}.\tag{59, 12}$$

Wir bemerken, daß die die Matrixelemente der Matrizen σ und s bestimmenden Indizes 1 und 2 jetzt (wo die Darstellung gewählt ist) sozusagen eine physikalische Bedeutung haben: Der Index 1 bezieht sich auf den ersten Eigenwert von $s_z \left(+\dfrac{h}{2}\right)$, der Index 2 auf den zweiten $\left(-\dfrac{h}{2}\right)$.

Wir wollen jetzt den Operator des Quadrates des Elektronenspins bilden. Aus (59, 2) folgt

$$s^2 = s_x^2 + s_y^2 + s_z^2 = \frac{3}{4} h^2 \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} = \frac{3}{4} h^2 \delta.\tag{59, 13}$$

Führen wir die Quantenzahlen m_s und l_s ein, die den Wert der Spinkomponente in einer beliebigen z-Richtung und dementsprechend auch sein Quadrat bestimmen, so können wir die Formeln für die Quantelung des Spins in Analogie zu den Formeln (51, 9; 51, 10) für das Bahnmoment aufstellen:

$$s^2 = h^2 l_s(l_s + 1), \quad l_s = \frac{1}{2},\tag{59, 14}$$

$$s_z = h m_s, \quad m_s = \pm \frac{1}{2}.\tag{59, 15}$$

231

5. Summary and conclusion

The Zeeman splitting of the 5876 Å helium lines is described by quantum mechanical calculations in the transition state between low-field approximation and Paschen–Back effect. Measurements by absorption spectroscopy, resonant scattering and saturated absorption technique prove the validity of the theoretical model. The optical diagnostic of the Zeeman splitting is a helpful tool in measuring the magnetic field strength.

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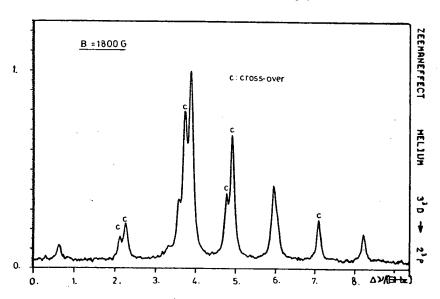
Fig. 9. Doppler-free spectrum of the $2\,^3P_0 \rightarrow 3\,^3D_1$ transition at B = 1800 G.

$3\,^3D_{2,+1}$ and $3\,^3D_{3,+1}$ eigenstates. The transition $3\,^3D_{2,1}-2\,^3P_{0,0}$ is thus forbidden only in the field-free case. Due to the large energy separation between the $2\,^3P_0$ and the remaining $2\,^3P_1$ levels of 30 GHz all σ transitions shown in fig. 9 can be related to the common lower level $2\,^3P_0$.

Summarizing, it can be derived from fig. 9 that the spectrum consists of six cross-over resonances in addition to the five σ transitions. Fig. 10 shows a comparison between the measured spectrum from fig. 9 and the calculated one. Because the cross-over resonances are not included in our calculations the calculated spectrum shows only the σ Zeeman transitions.
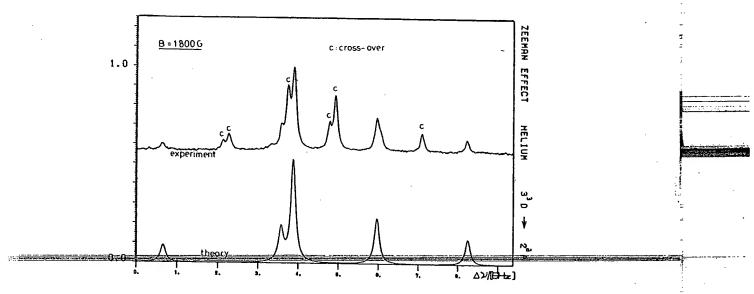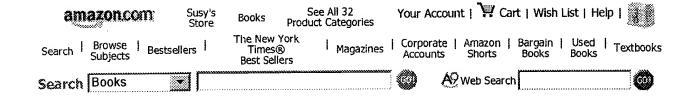
Fig. 10. Experimental spectrum of the Zeeman transition for B = 1800 G compared with the calculated one.

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Editorial Reviews

Shelby T. Brewer, former Assistant Secretary of Energy, top nuclear official in the Rea Administration
I grew up and was educated (1960s) in a time when Einstein's lifelong (but unattained) quest f(unified field theory was celebrated rather anecdotally, as a sort of historical curiosity. One spok theories as 'tools', or 'models'. The prevailing mentality was 'one model does not fit all.' A mode work and be useful in one set of circumstances but not another; use a model to get practical re a pursuit of absolute unifying truth was regarded largely as a waste of candle wax.

Other characteristics of this time in science were intolerance, arrogance, and rigidity. Scientists and postured, became intensely political, and delegated the 'doing' of science to students. Scien becoming big science - a big governmental and corporate enterprise - demanding more resourc becoming less accountable." We now have an expensive standing army in American science, mi place, with little creative, definable mission. Most of what passes for science is merely chauvini: has the largest accelerator, etc.

Now along comes Randell Mills. Without expending billions or even millions or even hundreds of thousands of US taxpayers' dollars, Dr. Mills has apparently completed Einstein's quest for a un theory. Dr. Mills' theory is presented in his book, *The Grand Unified Theory of Classical Quantur Mechanics* (November 1995).

This is a huge achievement for three reasons. First, the Mills Theory tidies up theoretical physic stitching together quantum mechanics and relativity. That in itself is a major triumph. Second, important, the Mills Theory explains several major empirical anomalies that have vexed physicis decades: the sun's energy balance deficit; the dark matter in space phenomena; and mountain: atomic-electron spectral data that is inconsistent with prevailing theory. Third, the Mills Theory to the possibility of an inexhaustible energy source based on phenomenology not yet recognizes accepted by the scientific community."

Remarkably, Dr. Mills has developed his theory and its energy generation application as an entr -- without largesse from the US Government, and without the benediction of the US scientific p Because his enterprise does not suffer these two impediments, it just might succeed. If so, Mills the next Thomas Edison.

Book Description
Physics Theory with Experimental Confirmation. Unification of Maxwell's Equations, Special, and Relativity.

About the Author
Dr. Mills, the founder and principal stockholder of the Company, has served as President, Direct Chairman of the Board since 1991. Dr. Mills received a Bachelor of Arts Degree in chemistry, su laude and Phi Beta Kappa from Franklin & Marshall College in 1982 and a Doctor of Medicine de Harvard Medical School in 1986. Following a year of graduate work in electrical engineering at t Massachusetts Institute of Technology, Dr. Mills began his research in the field of energy techn has authored or co-authored three articles in the field of energy technology that have been pub scientific journals, and a fourth publication is in progress. Dr. Mills has received or filed patents following areas: (1) magnetic resonance imaging; (2) Mossbauer cancer therapy; (3) Luminide drug delivery molecules; (4) genomic sequencing method, and (5) artificial intelligence. A thorc description of the company's technology and Dr. Mills' underlying atomic theory is published in entitled Unification of Spacetime, the Forces, Matter, and Energy (Science Press, 1992) and in t book entitled, *The Grand Unified Theory of Classical Quantum Mechanics*, Science Press, Noverr Edition and September 1996 Edition.

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Origin of quantum-mechanical complementarity probed by a 'which-way' experiment in an atom interferometer

ORIGINAL

S. Dürr, T. Nonn & G. Rempe

Fakultät für Physik, Universität Konstanz, 78457 Konstanz, Germany

The principle of complementarity refers to the ability of quantum-mechanical entities to behave as particles or waves under different experimental conditions. For example, in the famous double-slit experiment, a single electron can apparently pass through both apertures simultaneously, forming an interference pattern. But if a 'which-way' detector is employed to determine the particle's path, the interference pattern is destroyed. This is usually explained in terms of Heisenberg's uncertainty principle, in which the acquisition of spatial information increases the uncertainty in the particle's momentum, thus destroying the interference. Here we report a which-way experiment in an atom interferometer in which the 'back action' of path detection on the atom's momentum is too small to explain the disappearance of the interference pattern. We attribute it instead to correlations between the which-way detector and the atomic motion, rather than to the uncertainty principle.

In classical physics, a particle moves along a well-defined trajectory. A quantum object, however, reveals its wave character in interference experiments in which the object seems to move from one place to another along several different paths simultaneously. It is essential that these ways are indistinguishable, because any attempt to observe which way the object actually took unavoidably destroys the interference pattern.

The usual explanation for the loss of interference in a which-way experiment is based on Heisenberg's position–momentum uncertainty relation. This has been illustrated in famous *gedanken* experiments like Einstein's recoiling slit or Feynman's light microscope. In the light microscope, electrons are illuminated with light immediately after they have passed through a double slit with slit separation d. A scattered photon localizes the electron with a position uncertainty of the order of the light wavelength, $\Delta z \approx \lambda_{light}$. Owing to Heisenberg's position–momentum uncertainty relation, this localization must produce a momentum uncertainty of the order of $\Delta p_z \approx h/\lambda_{light}$. This momentum uncertainty arises from the momentum kick transferred by the scattered photon. For $\lambda_{light} < d$, which-way information is obtained, but the momentum kick is so large that it completely washes out the spatial interference pattern.

However, Scully *et al.*[3] have recently proposed a new *gedanken* experiment, where the loss of the interference pattern in an atomic beam is not related to Heisenberg's position–momentum uncertainty relation. Instead, the correlations between the which-way detector and the atomic beams are responsible for the loss of interference fringes.

Such correlations had already been studied experimentally. They are, for example, responsible for the lack of ground-state quantum beats in time-resolved fluorescence spectroscopy[4]. Other examples are neutron interferometers, where which-way information can be stored by selectively flipping the neutron spin in one arm of the interferometer[5,6].

Nevertheless, the *gedanken* experiment of Scully *et al.* was criticized by Storey *et al.*[7], who argued that the uncertainty relation always enforces recoil kicks sufficient to wash out the fringes. This started a controversial discussion[8-11] about the following question: "Is complementarity more fundamental than the uncertainty

principle?"[10]. This motivated Wiseman *et al.*[11] to investigate what constitutes a momentum transfer in a double-slit experiment. They call the usual momentum transfer, like that in Feynman's light microscope, a "classical" kick; in addition, they define the concept of "quantum" momentum transfer. They find that the loss of interference need not be due to "classical" kicks. In this case the "quantum" momentum transfer cannot be less than that required by the uncertainty principle, so that these "quantum" kicks wash out the fringes.

In this context, Eichmann *et al.*[] performed an experiment with a light interferometer, where the double slit is replaced by two trapped ions, which can store which-way information in internal states. This scheme was criticized, because the ions play a double role: they act as sources of elementary waves (just like a double slit) and simultaneously as a which-way detector. Hence the momentum transfer from the double slit and the which-way detector cannot be separated.

Here we report on a which-way experiment with an atom interferometer. A microwave field is used to store the which-way information in internal atomic states. We study the mechanical effect of the which-way detection on the atomic centre-of-mass motion separately, and find that the "classical" momentum kicks are much too small to wash out the interference pattern. Instead, correlations between the which-way detector and the atomic motion destroy the interference fringes. We show that the back action onto the atomic momentum implied by Heisenberg's position–momentum uncertainty relation cannot explain the loss of interference.

The atom interferometer
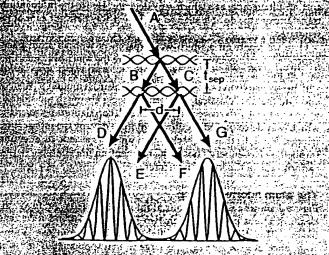
Figure 1 shows a scheme of our atom interferometer. An incoming beam of atoms passes through two separated standing wave light beams. The detuning of the light frequency from the atomic resonance, $\Delta = \omega_{light} - \omega_{atom}$, is large so that spontaneous emission can be neglected. The light fields each create a conservative potential U for the atoms, the so-called light shift, with $U \propto I/\Delta$, where I is the light intensity (see, for example, ref. 13). In a standing wave the light intensity is a function of position, $I(z) = I_0 \cos^2(k_{light} z)$, where k_{light} is the wavevector of the light. Hence the light shift potential takes the form $U(z) = U_0 \cos^2(k_{light} z)$, with $U_0 \propto I/\Delta$.

articles

The atoms are Bragg-reflected from this periodic potential, if they enter the standing light wave at a Bragg angle (see, for example, ref. 14). This process is similar to Bragg reflection of X-rays from the periodic structure of a solid-state crystal, but with the role of matter and light exchanged. In our experiment, the light creates the periodic structure, from which the matter wave is reflected.

The standing light wave splits the incoming atomic beam A (see Fig. 1) into two beams, a transmitted beam C and a first-order Bragg-reflected beam B. The angle between the beams B and C corresponds to a momentum transfer of exactly $2\hbar k_{light}$ as determined by the spatial period of $U(z)$. By varying the light intensity the fraction of reflected atoms can be adjusted to any arbitrary values. In our experiment, the reflectivity of the beam splitter is tuned to ~50%.

After switching off the first standing light wave, the two beams are allowed to propagate freely for a time interval t_{sep}. During this time, beam B moves a horizontal distance $d/2$ to the left and beam C moves $d/2$ to the right. The longitudinal velocities (vertical in Fig. 1) of the two beams are not affected by the light field. Then a second standing light wave is switched on, which also serves as a 50% beam splitter. Now two atomic beams D and E are travelling to the left, while beams F and G are travelling to the right. In the far field, each pair of overlapping beams produces a spatial interference pattern. The fringe period is the same as in a double-slit experiment with slit separation d. The relevant wavelength is the de Broglie wavelength associated with the momentum of the atoms. The envelope of the fringe pattern is given by the collimation properties of the initial atomic beam A.

The experiment is performed with the apparatus described in ref. 15. Rb atoms are loaded into a magneto-optical trap (MOT). After trapping and cooling, the cloud of atoms is released and falls freely through the apparatus. The resulting pulsed atomic beam is collimated with a mechanical slit 20 cm below the MOT. The atoms then pass the interaction region with the standing light wave inside a microwave resonator. In the far field of the interaction region 45 cm below the MOT, the atomic position distribution is observed by exciting the atoms with a resonant laser beam and detecting the fluorescence photons. The interaction time t_{int} of the atoms with the standing light wave is controlled by switching the light on and off. The small atomic velocity of 2 m s⁻¹ in the

interaction region allows us to perform the whole interferometer experiment with only one standing light wave, which is switched on and off twice. As compared to ref. 15, only a few changes have been made. The width of the collimation slit was enlarged to 450 μm. In order to improve the position resolution, the horizontal waist of the detection laser beam was reduced to $w = 50$ μm, and a second collimation slit with a width of 100 μm was added 1 cm below the MOT. Finally, the preparation of the internal atomic state was improved by removing atoms in wrong Zeeman sublevels.

Figure 2 shows the spatial fringe pattern in the far field for two different values of t_{sep}. We note that the observed far-field position distribution is a picture of the atomic transverse momentum distribution after the interaction.

Storing which-way information

A second quantum system is now added to the interferometer in order to store the information whether the atom moved along way B

Figure 1 Scheme of the atom interferometer. The incoming atomic beam A is split into two beams: beam C is transmitted and beam B is Bragg-reflected from a standing light wave. The beams are not exactly vertical, because a Bragg condition must be fulfilled. After free propagation for a time t_{sep} the beams are displaced by a distance d. Then the beams are split again with a second standing light wave. In the far field, a spatial interference pattern is observed.
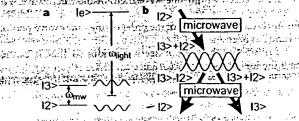
Figure 2 Spatial fringe pattern in the far field of the interferometer. The data were obtained with $t_{int} = 45$ μs, and the 50% beam splitter was realized with $|U_0| = \hbar\pi/t_{int}$. We chose $t_{sep} = 105$ μs with $d = 1.3$ μm (a), and $t_{sep} = 255$ μs with $d = 3.1$ μm (b). In both cases, the fringe period is in good agreement with the theoretical expectation. Each solid line represents a fit to the experimental data. The best-fit values for the visibilities are (75 ± 1)% and (44 ± 1)% respectively. The reduced visibility for the case of the narrow fringes is due to the finite position resolution of our apparatus. The dashed lines represent the independently measured beam envelope, which consists of two broad peaks. The right peak is due to beams F and G (see Fig. 1), with a shape determined by the momentum distribution of the initial beam A. The left peak is a combination of beams D and E. It is a Bragg-reflected picture of the right peak. The fringe patterns under these two broad peaks are complementary, that is, the interference maxima in the left peak correspond to interference minima in the right peak, and vice versa.

or C. Two internal electronic states of the atom are used as a which-way detector system. A simplified level scheme of ⁸⁵Rb is shown in Fig. 3a. Rabi oscillations between states |2⟩ and |3⟩ can be induced by applying a microwave field at ~3 GHz. To describe the information storing process, we first investigate the properties of one single Bragg beam splitter, using a simple model, whose validity will be discussed later.

The frequency of the standing light wave, ω_{light}, is tuned halfway between the |2⟩ → |e⟩ and |3⟩ → |e⟩ transitions. Hence the detunings from these transitions, Δ_2 and Δ_3, have the same absolute value but opposite sign. The reflectivity of the beam splitter, that is, the probability of reflecting an atom, depends on $t_{Bragg} \times |U_0|$, and it is independent of the internal state.

However, the amplitude of the wavefunction experiences a phase shift which depends on the internal atomic state. A simple analogy for this phase shift can be found in light optics: a light wave reflected from an optically thicker medium experiences a phase shift of π, while reflection from an optically thinner medium or transmission into an arbitrary medium does not cause any phase shift. This argument also applies in atom optics: in our experiment, an atom in |2⟩ sees a negative light shift potential (because $\Delta_2 < 0$), corresponding to an optically thicker medium, while an atom in |3⟩ sees a positive potential (because $\Delta_3 < 0$), corresponding to an optically thinner medium. Hence an atom will experience a π phase shift only if it is reflected in |2⟩.

This phase shift can be converted into a population difference between the hyperfine levels. For that purpose two microwave $\pi/2$ pulses resonant with the hyperfine transition are applied. They form a Ramsey scheme as shown in Fig. 3b. The atom is initially prepared in state |2⟩. Then a microwave $\pi/2$ pulse is applied, converting the internal state to the superposition state $(|3⟩ + |2⟩)/\sqrt{2}$. After this, the atom interacts with the standing light wave. As explained above, the atom will experience a π phase shift only if it is reflected and in state |2⟩. Thus the internal state of the reflected beam is changed to $(|3⟩ + |2⟩)/\sqrt{2}$, while the internal state of the transmitted beam is not affected. As a result, there is an entanglement created between the internal and the external degree of freedom of the atom. The state vector of the system becomes:

$$|\psi⟩ \propto |\psi_B⟩ \otimes (|3⟩ - |2⟩) + |\psi_C⟩ \otimes (|3⟩ + |2⟩) \qquad (1)$$

where $|\psi_B⟩$ and $|\psi_C⟩$ describe the centre-of-mass motion for the reflected and transmitted beams (see Fig. 1), respectively. This entanglement is the crucial point for the storage of information. The second microwave pulse acting on both beams (the transmitted and the reflected), converts the internal state of the transmitted beam to state |3⟩, while the reflected beam is converted to state

|2⟩. Thus, the state vector after the pulse sequence shown in Fig. 3b becomes:

$$|\psi⟩ \propto |\psi_B⟩ \otimes |2⟩ + |\psi_C⟩ \otimes |3⟩ \qquad (2)$$

We note that momentum transfer from the microwave slightly changes $|\psi_B⟩$ and $|\psi_C⟩$, but this has negligible effects, as will be discussed below.

Equation (2) shows that the internal state is correlated with the way taken by the atom. The which-way information can be read out later by performing a measurement of the internal atomic state. The result of this measurement reveals which way the atom took: if the internal state is found to be |2⟩, the atom moved along beam B, otherwise it moved along beam C.

A detailed calculation of the beam splitter reveals an additional phase shift, not discussed so far. It arises because the atoms travel in the light shift potential during t_{Bragg}. This creates a phase shift for the atoms proportional to $U_0 \times t_{Bragg}$, resulting in a relative phase shift between atoms in states |2⟩ and |3⟩. Fortunately, this phase shift is identical for the transmitted and reflected beams and therefore does not affect the storing process in an essential manner. Moreover, a small detuning of the microwave frequency from the atomic resonance allows us to compensate for this effect, so that the simple model discussed above is valid.

Interferometer with which-way information

After considering a single beam splitter, we now return to the complete interferometer. Sandwiching the first Bragg beam splitter between two microwave $\pi/2$ pulses stores the which-way information in the internal atomic state, as described above. We note that the second Bragg beam splitter does not change the internal state. Will there still be interference fringes in the far field when the which-way information is stored? The experimental result is shown in Fig. 4: there are no fringes. The data were recorded with the same parameters as in Fig. 2a. The only difference is that two microwave pulses were added to store the which-way information. Atoms in both hyperfine states were detected, so that the which-way detector was not read out. The mere fact that which-way information is stored in the detector and could be read out already destroys the interference pattern. We have verified experimentally that the fringes also disappear when the which-way detector is read out, that is, when only atoms in state |2⟩ or only atoms in state |3⟩ are detected. Of course, the absolute size of the signal is reduced by a factor of two in these cases.

Mechanical effects

We now discuss whether the loss of interference can be explained by mechanical effects of the which-way detector on the atomic

Figure 3 Storage of which-way information. a, Left, simplified level scheme of ⁸⁵Rb. The excited state $(5^2P_{3/2})$ is labelled |e⟩. The ground state $(5^2S_{1/2})$ is split into two hyperfine states with total angular momentum $F = 2$ and $F = 3$, which are labelled |2⟩ and |3⟩, respectively. Right, the standing light wave with angular frequency ω_{light} induces a light shift for both ground states which is drawn as a function of position. b, The beam splitter produces a phase shift that depends on the internal and external degree of freedom. A Ramsey scheme, consisting of two microwave $\pi/2$ pulses, converts this phase shift into a population difference (see text).
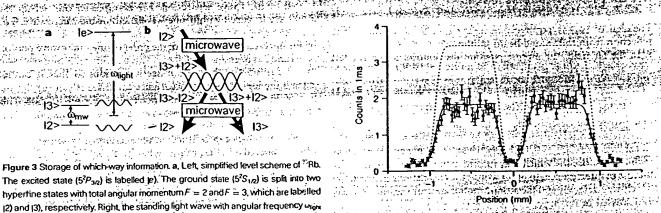

Figure 4 Same as Fig. 2a, but with which-way information stored in the internal atomic state. The interference fringes are lost due to the storage of which-way information.

centre-of-mass motion. Therefore the transverse momentum transfer in the microwave field and the longitudinal displacement of the atomic wavefunction must be investigated.

To wash out the interference fringes, the transverse momentum transfer must have a distribution whose spread must correspond to at least half a fringe period. Such a "classical" momentum transfer distribution would also broaden the envelope of the fringe pattern by the same amount". Comparing the experimental data in Fig. 2a and Fig. 4, it is obvious that the width of the envelope is not changed. This experimental result clearly shows that there is no significant transfer of transverse momentum in the microwave field.

The momentum transfer during the interaction with the microwave field can also be estimated theoretically. The microwave field is a standing wave diffracting the atomic beam. Because the atoms are travelling much less than a microwave wavelength during the interaction, the Raman–Nath approximation is valid. For a plane atomic wave, the probability to pick up n photon momenta during a $\pi/2$ pulse is $J_n^2(\pi/2)$, where J_n is the nth-order Bessel function[15]. Hence the probability of transferring more than two microwave photon momenta is less than 1%. The absorption of a single microwave photon shifts the position of the atom in the detector plane by 5 nm. It follows that the mechanical recoils during the interaction with the microwave field can shift the pattern by at most ± 10 nm—too small to be observed. Of course, the transverse width of the atomic beam is much less than a microwave wavelength so that the atomic beam is not a plane wave. However, the atomic beam is a superposition of plane waves. The above Raman–Nath calculation applies for each plane wave component, so that the spread of the atomic beam cannot be larger than for a plane wave.

The second mechanical effect that could explain the loss of interference is a longitudinal displacement of the atomic wavefunction as discussed in ref. 7. In our experiment, this argument does not apply because the whole interaction sequence is pulsed. The atom's potential energy varies as a function of time, not as a function of longitudinal position, so that the interaction does not create any longitudinal forces and displacements.

We conclude that the "classical" mechanical effects of the which-way detector on the atomic centre-of-mass motion are negligible, so that some other mechanism must enforce the loss of interference fringes.

Correlations destroy interference

In order to investigate why the interference is lost, we consider the state vector for the interaction sequence used in Fig. 4. The state vector after the interaction with the first beam splitter sandwiched between the two microwave pulses is given in equation (2). The second beam splitter transforms this state vector into:

$$|\psi\rangle \propto -|\psi_D\rangle \otimes |2\rangle + |\psi_E\rangle \otimes |3\rangle + |\psi_F\rangle \otimes |2\rangle + |\psi_G\rangle \otimes |3\rangle. \quad (3)$$

The sign of $|\psi_F\rangle$ is positive due to the π phase shift during the reflection from the second beam splitter.

In the far field, the atomic position distribution under the left peak of the envelope is given by:

$$P(z) \propto |\psi_D(z)|^2 + |\psi_E(z)|^2 - \psi_D(z)\psi_E(z)\langle 2|3\rangle - \psi_E(z)\psi_D(z)\langle 3|2\rangle \quad (4)$$

because here the spatial wavefunctions $\psi_F(z)$ and $\psi_G(z)$ vanish. The first two terms describe the mean intensity under the envelope. Interference could only be created by the last two terms, but they vanish because $\langle 2|3\rangle = 0$. Precisely the same entanglement that was required to store the which-way information is now responsible for the loss of interference. In other words: the correlations between the which-way detector and the atomic motion destroy the interference, as discussed in ref. 3.

This loss of interference manifests itself as a dramatic change in the momentum distribution when adding the microwave fields to the interferometer, even though the microwave itself does not transfer enough momentum to the atom to wash out the fringes.

However, the addition of the microwave fields modifies the probability for momentum transfer by the light fields. This modification of the momentum transfer probability is due to the correlations between the which-way detector and the atomic motion. Correlations between the interfering particle and the detector system are produced in any which-way scheme, for example, in the previously mentioned gedanken experiments of Einstein's recoiling slit and Feynman's light microscope. But in these experiments "classical" mechanical effects of the detector on the particle's motion can explain the loss of interference as well, so that the effect of the correlations is hidden.

So far, the microwave field has been treated as a classical field, that is, not as a quantized field. At first glance this might seem to be unjustified, because the population difference between the two hyperfine states corresponds to the absorption of one microwave photon, so that the system also becomes entangled with the microwave field. Hence the interference terms in equation (4) must include an additional factor $\langle \alpha|\beta \rangle$, where $|\alpha\rangle$ denotes the initial state of the microwave field, which changes to $|\beta\rangle$ due to the absorption of one photon. In our experiment, the initial state $|\alpha\rangle$ is a coherent state with a large mean photon number, and therefore the spread of the photon number is also large. It follows that $\langle \alpha|\beta \rangle \approx 1$ so that the entanglement with the microwave field has negligible effects, as has already been pointed out in ref. 3.

Uncertainty relation

We now discuss the role of Heisenberg's position–momentum uncertainty relation in our experiment. For this discussion it is essential that the two ways through the interferometer (beams B and C in Fig. 1) are never separated in transverse position space. This is because the beams have a transverse width of 450 μm (as determined by the width of the lower collimation slit), but are shifted transversely only by a few micrometres (given by d) with respect to each other. This has an important consequence: the storage of which-way information does not imply any storage of transverse position information.

Moreover, the atom is not localized with a precision of the order of d at any stage of the experiment. In particular, the atom stays delocalized during its whole passage through the interaction region, regardless of whether the microwave is on or off. Heisenberg's position–momentum uncertainty relation could only be invoked if the atom were localized. Hence the uncertainty relation does not imply any back action onto the transverse momentum, either "classical" or quantum.

Of course, in every real experiment there are localization effects due to the finite size of the apparatus. This localization leads to a back action onto the momentum. But this back action is not at all related to the fringe separation. For example, in our set-up the atoms are localized within one wavelength of the microwave. The corresponding back action onto the transverse momentum implied by the uncertainty relation is of the order of one microwave photon recoil and has been analysed above. This back action is four orders of magnitude smaller than the fringe separation, so that it cannot explain the loss of interference. Hence correlations can explain the loss of interference, while the uncertainty relation cannot. This answers the controversial question cited in the introduction: complementarity is not enforced by the uncertainty relation.

This result is not in conflict with the results of Wiseman et al., who considered only experiments in which double-slit interference patterns are destroyed by making a position measurement. In our experiment, no double slit is used and no position measurement is performed, so that the results of ref. 11 do not apply. It is an open question whether the concept of "quantum" momentum transfer can be generalized to schemes without a mechanical double slit. Such a generalization would have to take into account the fact that in our experiment, the amount of momentum transferred by the light fields is always either zero or exactly $2\hbar k$.

Although beams B and C are never separated in transverse position space, they are separated in transverse momentum space. The separation is $2\hbar k_{light}$, as is required for first-order Bragg reflection. Storing which-way information therefore corresponds to storing transverse momentum information with an accuracy of the order of $\Delta p_z \approx \hbar k_{light}$. So the uncertainty relation implies that the storing process must include a back action onto the transverse position of the order of $\Delta z \approx \lambda_{light}$. This back action is due to the following effect. In the Bragg regime, the interaction time with the standing light wave, t_{Bragg}, is so long that the atoms move at least a transverse distance of the order of $\lambda_{light}/2$ within t_{Bragg}. In a wave picture, the atoms can be Bragg-reflected at the beginning or at the end of this interaction, which implies a transverse position uncertainty of the order of $\Delta z \approx \lambda_{light}$. But this back action onto the near-field position cannot destroy the far-field fringe pattern. The interference pattern created in the interferometer is a pattern in momentum space, not in position space. The far-field position distribution is simply a picture of the final momentum distribution. □

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A critical window for cooperation and competition among developing retinotectal synapses

Li I. Zhang*, Huizhong W. Tao*, Christine E. Holt†, William A. Harris† & Mu-ming Poo

Department of Biology, University of California at San Diego, La Jolla, California 92093-0357, USA
* These authors contributed equally to this work

In the developing frog visual system, topographic refinement of the retinotectal projection depends on electrical activity. *In vivo* whole-cell recording from developing *Xenopus* tectal neurons shows that convergent retinotectal synapses undergo activity-dependent cooperation and competition following correlated pre- and postsynaptic spiking within a narrow time window. Synaptic inputs activated repetitively within 20 ms before spiking of the tectal neuron become potentiated, whereas subthreshold inputs activated within 20 ms after spiking become depressed. Thus both the initial synaptic strength and the temporal order of activation are critical for heterosynaptic interactions among convergent synaptic inputs during activity-dependent refinement of developing neural networks.

Electrical activity in the developing nervous system plays a crucial role in the establishment of early nerve connections[1,2]. In the mammalian visual system, both the formation of ocular dominance columns in the primary visual cortex[3–5] and the segregation of retinal ganglion axons into eye-specific layers in the lateral geniculate nucleus[6] depend on electrical activity in the visual pathways. The pattern of activity in the optic nerves seems to serve an instructive role, as synchronous stimulation of optic nerves abolishes the formation of ocular dominance columns, whereas asynchronous stimulation leads to sharp ocular dominance columns[7]. Artificially synchronized activity in the optic nerve also disrupts the development of orientation tuning in the visual cortex[8]. In the visual system of frog, chick and fish, retinal axons use activity-independent mechanisms initially to establish a topographic map,

but the initial map is coarse and terminals from each retinal axon arborize over a large portion of the tectum. During development, the map becomes refined as retinal axons progressively restrict their arborizations to a smaller fraction of the tectum[9,10]. Topographic refinement of the retinotectal projection also depends on activity patterns, as this process is impaired when retinal activity is blocked or uniformly synchronized by raising the animals in strobe light[11–14]. Thus, throughout the visual system, the refinement of connections depends on the pattern of activity, but the underlying physiological mechanisms are largely unknown.

We have examined quantitatively the effects of activity patterns on the strength of developing central synapses in the *Xenopus* retinotectal system. *In vivo* whole-cell recordings were made from neurons in the optic tectum of young *Xenopus* tadpoles to monitor changes in the strength of retinotectal synapses following repetitive electrical stimulation of retinal neurons in the contralateral eye. By

† Present address: Department of Anatomy, University of Cambridge, Cambridge CB2 3DY, UK.

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Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)
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Description

A large area or microfocused pulsed primary ion beam sputters the top surface layer of the sample. The secondary ions produced in this sputtering process are extracted from the sample surface and injected into a specially designed time-of-flight mass spectrometer. The ions are dispersed in time according to their velocity (which is proportional to their mass-to-charge ratio m/z) and the discrete packets of different massed ions are detected on either a microchannel plate (MCP) or resistive anode encoder (RAE) detector. The TOF SIMS technique is capable of detecting secondary ions produced over a large mass range (typically 0 to around 5000 atomic mass units) and performs this mass analysis at relatively high mass resolutions (>6000 m/Δm). The technique also is capable of generating an image of the lateral distributions of these secondary ions at spatial resolutions of better than _**0.15 microns**_.

Specimen Requirements

- Conductors or insulators
- <200 mm diameter
- <12.5 mm thick
- Vacuum compatible

Unique Advantages

- Rapid, non-destructive, sensitive elemental, inorganic and organic compound analysis of top monolayer of a surface
- Imaging analysis of the lateral distribution of selected secondary ions
- High mass range, resolution, and mass accuracy determinations

X-Ray Photoelectron Spectroscopy (XPS)
Electron Spectroscopy for Chemical Analysis (ESCA)
http://www.cea.com/inst.htm#esca2

Description

Samples are irradiated with monochromatic X-rays which cause the ejection of photoelectrons from the surface. The electron binding energies, as measured by a high resolution electron spectrometer, are used to identify the elements present and, in many cases, provide information about the valence state(s) or chemical bonding environment(s) of the elements thus detected. The depth of the analysis, typically the outer _**3 nm**_ of the sample, is determined by the escape depth of the photoelectrons and the angle of the sample plane relative to the spectrometer.

Specimen Requirements
- Conductors or insulators
- up to 95mm diam. or 75mm on the side
- up to 20mm thick
- Vacuum compatible

Unique Advantages
- Determination of valence states and/or bonding environment of atoms near the surface
- Convenient and quick elemental analysis of surfaces
- Identifies organic functional groups in polymer or other organic surfaces
- Analysis of surfaces of polymers subjected to surface modification treatment or processes
- Characterization of very thin surface layered structures
- Depth profiling or both conducting and insulating materials

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XPS (ESCA) - --- SAM

XPS and SAM are the primary instrumental methods to determine the elemental composition of surfaces. XPS stands for X-ray Photoelectron Spectroscopy, and is also known as ESCA (Electron Spectroscopy for Chemical Analysis). SAM stands for Scanning Auger Microscopy.

Besides surface composition XPS also gives information about an element's valence/oxidative state and chemical environment. SAM can provide microscopic images of the surface, and can pinpoint the surface location of elements (i.e., elemental maps). Typical analysis depth for XPS-SAM experiments is 20-30 angstroms (slightly more for polymers). All elements can be analyzed except for hydrogen and helium.

Principles
XPS - Samples are irradiated by a soft x-ray source causing direct ejection of core level electrons from surface atoms. These electrons are energy analyzed in a high resolution analyzer, producing an emission spectrum of peaks on a sloping background. Every element has its own unique XPS spectrum. *XPS peak positions are not fixed, but will shift depending on the valence/oxidation state of the atom and its chemical environment.*

SAM - A finely focused beam of electrons sweeps the sample, causing ?excitation? of surface atoms. During de-excitation, characteristic core level Auger electrons are produced (by Auger process). These electrons are energy analyzed in the same analyzer used for XPS. Because Auger peaks are usually weaker and broader than XPS peaks, spectra are usually recorder in derivative form. High resolution microscopic images and surface maps can also be produced.

Depth profile analysis can be performed by using a sputter-etch gun with either XPS or SAM. The sputter rate is approximately 16 angstroms/minute.

Applications
Catalysts - foe elemental surface composition, oxidation states, and poisoning. Polymers - for surface composition, blooms, oxidation, depth profiles, stains, surfactant coverage, surface treatments, adhesion and interface problems, etc. Tire wire cords - for surface composition, depth profiles, plating thickness uniformity, plating voids, adhesion and interface problems.

In XPS mode, the normal sample size is 1 X 4 mm. Samples as small as 1000?m can be analyzed. For smaller areas (200-600 ?m) we have access to a Physical Electronics (PHI) 5300 instrument at a local university.

✎ *Sample Requirements*
Normal samples are solids such as metals, powders, and polymers. Most liquid samples can be made vacuum worthy using the BFG prefreeze glove box.

✎ *Limitations*
Samples for surface analysis must be kept free of contamination.
Both XPS and SAM are semi-quantitative. Data can be processed to give either atomic weight or weight percent results. One of the best ways to use XPS and SAM is to compare ?good? and ?bad? samples.

XPS has the greatest range of general application. Specimen damage is very low, and virtually any solid sample can be analyzed, such as: rubbers, polymers, polymer additives, metals, catalysts, interfaces, composites, etc. Frozen liquids can also be analyzed.

SAM is best applied to solid conducting samples such as metals. Polymers usually cannot be analyzed as the electron beam almost instantly damages the surface and generates surface charging which distorts images and spectra. Limited application is possible with catalysts, but sample charging problems restrict sensitivity, resolution, and signal-to-noise ratio.

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Research Article
X-ray photoelectron spectroscopy studies of CVD diamond films

Y. Fan [1] [*], A. G. Fitzgerald [1], P. John [2], C. E Troupe [2], J. I. B. Wilson [3]

[1] Department of Electronic Engineering and Physics, University of Dundee, Dundee DD1 4HN, UK

[2] Department of Chemistry, Heriot-Watt University, Edinburgh EH14 4AS, UK

[3] Department of Physics, Heriot-Watt University, Edinburgh EH14 4AS, UK

email: Y. Fan (y.fan@dundee.ac.uk)

[*] Correspondence to Y. Fan, Department of Electronic Engineering and Physics, University of Dundee, Dundee DD1 4HN, UK.

Abstract

In this research work, a comparative x-ray photoelectron spectroscopy (XPS) analysis has been performed on three allotropic carbon materials i.e. amorphous carbon films, graphite crystals and chemically vapour deposited (CVD) diamond films. These studies have shown that XPS is one of the most powerful techniques used to distinguish the diamond phase of carbon from the graphite and amorphous carbon components. In these investigations, particular attention has been paid to the effects of the post-deposition surface treatment on the diamond surfaces and the corresponding spectrum changes. The experimental results confirmed that ion surface cleaning destroys the original carbon atomic bonding configuration and implants argon atoms into the sample surface. The main spectral changes for amorphous carbon, graphite and diamond materials after the ion etching process can be attributed to bonding modification and the existence of argon contamination on the sample surfaces. Copyright © 2002 John Wiley & Sons, Ltd.

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Television, the movies, and computer games fill the minds of their viewers with a daily staple of fantasy, from tales of UFO landings, haunted houses, and communication with the dead to claims of miraculous cures by gifted healers or breakthrough treatments by means of fringe medicine. The paranormal is so ubiquitous in one form of entertainment or another that many people easily lose sight of the distinction between the real and the imaginary, or they never learn to make the distinction in the first place. In this thorough review of pseudoscience and the paranormal in contemporary life, psychologist Terence Hines teaches readers how to carefully evaluate all such claims in terms of scientific evidence.

Hines devotes separate chapters to psychics; life after death; parapsychology; astrology; UFOs; ancient astronauts, cosmic collisions, and the Bermuda Triangle; faith healing; and more. New to this second edition are extended sections on psychoanalysis and pseudopsychologies, especially recovered memory therapy, satanic ritual abuse, facilitated communication, and other questionable psychotherapies. There are also new chapters on alternative medicine, which is now marketed in our drug stores, and on environmental pseudoscience, with special emphasis on the evidence that certain technologies like cell phones or environmental agents like asbestos cause cancer.

Finally, Hines discusses the psychological causes for belief in the paranormal despite overwhelming evidence to the contrary. This valuable, highly interesting, and completely accessible analysis critiques the whole range of current paranormal claims.

Terence M. Hines (Pleasantville, NY) is professor of psychology at Pace University, and the author of the first edition of *Pseudoscience and the Paranormal*.

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◣ OPINION ◥

Quantum Theory Needs No 'Interpretation'

Christopher A. Fuchs and Asher Peres

Recently there has been a spate of articles, reviews, and letters in PHYSICS TODAY promoting various "interpretations" of quantum theory (see March 1998, page 42; April 1998, page 38; February 1999, page 11; July 1999, page 51; and August 1999, page 26). Their running theme is that from the time of quantum theory's emergence until the discovery of a particular interpretation, the theory was in a crisis because its foundations were unsatisfactory or even inconsistent. We are seriously concerned that the airing of these opinions may lead some readers to a distorted view of the validity of standard quantum mechanics. If quantum theory had been in a crisis, experimenters would have informed us long ago!

Our purpose here is to explain the internal consistency of an "interpretation without interpretation" for quantum mechanics. Nothing more is needed for using the theory and understanding its nature. To begin, let us examine the role of experiment in science. An experiment is an active intervention into the course of Nature: We set up this or that experiment to see how Nature reacts. We have learned something new when we can distill from the accumulated data a compact description of all that was seen and an indication of which further experiments will corroborate that description. This is what science is about. If, from such a description, we can *further* distill a model of a freestanding "reality" independent of our interventions, then so much the better. Classical physics is the ultimate example of such a model. However, there is no logical necessity for a realistic worldview to always be obtainable. If the world is such that we can never identify a reality independent
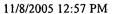
CHRIS FUCHS, *previously the Lee DuBridge Prize Postdoctoral Fellow at Caltech, is now a Director-Funded Fellow at Los Alamos National Laboratory. His daytime research focuses on quantum information theory and quantum computation.* ASHER PERES *is the Gerard Swope Distinguished Professor of Physics at Technion—Israel Institute of Technology, in Haifa, Israel. He is the author of* Quantum Theory: Concepts and Methods *(Kluwer, Dordrecht, 1993).*

of our experimental activity, then we must be prepared for that, too.

The thread common to all the nonstandard "interpretations" is the desire to create a new theory with features that correspond to some reality independent of our potential experiments. But, trying to fulfill a classical worldview by encumbering quantum mechanics with hidden variables, multiple worlds, consistency rules, or spontaneous collapse, without any improvement in its predictive power, only gives the illusion of a better understanding. Contrary to those desires, quantum theory does *not* describe physical reality. What it does is provide an algorithm for computing *probabilities* for the macroscopic events ("detector clicks") that are the consequences of our experimental interventions. This strict definition of the scope of quantum theory is the only interpretation ever needed, whether by experimenters or theorists.

Quantum probabilities, like all probabilities, are computed by using any available information. This can include, but is not limited to information about a system's preparation. The mathematical instrument for turning the information into statistical predictions is the probability rule postulated by Max Born.[1] The conclusiveness of Born's rule is known today to follow from a theorem due to Andrew Gleason.[2] It is enough to assume that yes–no tests on a physical system are represented by projection operators P, and that probabilities are additive over orthogonal projectors. Then there exists a density matrix ρ describing the system such that the probability of a "yes" answer is $\mathrm{tr}(\rho P)$. The compendium of probabilities represented by the "quantum state" ρ captures everything that can meaningfully be said about a physical system.

Here, it is essential to understand that the validity of the statistical nature of quantum theory is not restricted to situations where there are a large number of similar systems. Statistical predictions do apply to single events. When we are told that the probability of precipitation tomorrow is 35%, there is only one tomorrow. This tells us that it is advisable to

carry an umbrella. Probability theory is simply the quantitative formulation of how to make rational decisions in the face of uncertainty.

We do not deny the possible existence of an objective reality independent of what observers perceive. In particular, there is an "effective" reality in the limiting case of macroscopic phenomena like detector clicks or planetary motion: Any observer who happens to be present would acknowledge the objective occurrence of these events. However, such a macroscopic description ignores most degrees of freedom of the system and is necessarily incomplete. Can there also be a "microscopic reality" where every detail is completely described? No description of that kind can be given by quantum theory, nor by any other reasonable theory. John Bell formally showed[3] that any objective theory giving experimental predictions identical to those of quantum theory would necessarily be nonlocal. It would eventually have to encompass everything in the universe, including ourselves, and lead to bizarre self-referential logical paradoxes. The latter are not in the realm of physics; experimental physicists never need bother with them.

We have experimental evidence that quantum theory is successful in the range from 10^{-19} to 10^{15} atomic radii; we have no evidence that it is universally valid. Yet, it is legitimate to attempt to extrapolate the theory beyond its present range, for instance, when we probe particle interactions at superhigh energies, or in astrophysical systems, including the entire universe. Indeed, a common question is whether the universe has a wavefunction. There are two ways to understand this. If this "wavefunction of the universe" has to give a complete description of everything, including ourselves, we again get the same meaningless paradoxes. On the other hand, if we consider just a few collective degrees of freedom, such as the radius of the universe, its mean density, total baryon number, and so on, we can apply quantum theory only to these degrees of freedom, which do not include ourselves and other insignificant details. This is not essentially

different from quantizing t' ... the electric cu... in a ... the atomic details. For sure, we can manipulate a SQUID more easily than we can manipulate the radius of the universe, but there is no difference in principle.

Does quantum mechanics apply to the observer? Why would it not? To be quantum mechanical is simply to be amenable to a quantum description. Nothing in principle prevents us from quantizing a colleague, say. Let us examine a concrete example: The observer is Cathy (an experimental physicist) who enters her laboratory and sends a photon through a beam splitter. If one of her detectors is activated, it opens a box containing a piece of cake; the other detector opens a box with a piece of fruit. Cathy's friend Erwin (a theorist) stays outside the laboratory and computes Cathy's wavefunction. According to him, she is in a 50/50 superposition of states with some cake or some fruit in her stomach. There is nothing wrong with that; this only represents his knowledge of Cathy. She knows better. As soon as one detector was activated, her wavefunction collapsed. Of course, nothing dramatic happened to her. She just acquired the knowledge of the kind of food she could eat. Some time later, Erwin peeks into the laboratory. Thereby he acquires new knowledge, and the wavefunction he uses to describe Cathy changes. From this example, it is clear that a wavefunction is only a mathematical expression for evaluating probabilities and depends on the knowledge of whoever is doing the computing.

Cathy's story inevitably raises the issue of reversibility; after all, quantum dynamics is time-symmetric. Can Erwin undo the process if he has *not yet* observed Cathy? In principle he can, because the only information Erwin possesses is about the consequences of his potential experiments, not about what is "really there." If Erwin has performed no observation, then there is no reason he cannot reverse Cathy's digestion and memories. Of course, for that he would need complete control of all the microscopic degrees of freedom of Cathy and her laboratory, but that is a practical problem, not a fundamental one.

The peculiar nature of a quantum state as representing information is strikingly illustrated by the quantum teleportation process.[4] In order to teleport a quantum state from one photon to another, the sender (Alice) and the receiver (Bob) need to divide between them a pair of photons in a standard entangled state. The experiment begins when Alice receives another photon whose polarization state is unknown to her but known to a third-party preparer. She performs a measurement on her two photons—one from the original, entangled pair and the other in a state unknown to her—and then sends Bob a classical

"What do you mean, 'a quantum fluctuation?' Didn't we discuss cause and effect?"

message of only two bits, instructing him how to reproduce that unknown state on his photon. This economy of transmission appears remarkable, because to completely specify the state of a photon, namely one point in the Poincaré sphere, we need an infinity of bits. However, this complete specification is *not* what is transferred. The two bits of classical information serve only to convert the preparer's information, from a description of the original photon to a description of the one in Bob's possession. The communication resource used up for doing that is the correlated pair that was shared by Alice and Bob.

It is curious that some well-intentioned theorists are willing to abandon the objective nature of physical "observables," and yet wish to retain the abstract quantum state as a surrogate reality. There is a temptation to believe that every quantum system has a wavefunction, even if the wavefunction is not explicitly known. Apparently, the root of this temptation is that in classical mechanics *phase space* points correspond to objective data, whereas in quantum mechanics *Hilbert space* points corre-

nd to quantum states. This analogy is misleading: Attributing reality to quantum states leads to a host of "quantum paradoxes." These are due solely to an incorrect interpretation of quantum theory. When correctly used, quantum theory never yields two contradictory answers to a well-posed question. In particular, no wavefunction exists either before or after we conduct an experiment. Just as classical cosmologists got used to the idea that there is no "time" before the big bang or after the big crunch, so too must we be careful about using "before" and "after" in the quantum context.

Quantum theory has been accused of incompleteness because it cannot answer some questions that appear reasonable from the classical point of view. For example, there is no way to ascertain whether a single system is in a pure state or is part of an entangled composite system. Furthermore, there is no dynamical description for the "collapse" of the wavefunction. In both cases the theory gives no answer because the wavefunction is not an objective entity. Collapse is something that happens in our description of the system, not to the system itself. Likewise, the time dependence of the wavefunction does not represent the evolution of a physical system. It only gives the evolution of our probabilities for the outcomes of potential experiments on that system. This is the only meaning of the wavefunction.

All this said, we would be the last to claim that the foundations of quantum theory are not worth further scrutiny. For instance, it is interesting to search for minimal sets of *physical* assumptions that give rise to the theory. Also, it is not yet understood how to combine quantum mechanics with gravitation, and there may well be important insight to be gleaned there. However, to make quantum mechanics a useful guide to the phenomena around us, we need nothing more than the fully consistent theory we already have. Quantum theory needs no "interpretation."

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Matter all in the mind

Kurt Gottfried

In the autumn of 1925, Paul Adrien Maurice Dirac, a Cambridge University graduate student of very few words, astonished the world of physics with a remarkable paper on quantum mechanics. His publication heralded the arrival of a mind of exceptional originality and power at the frontier of physics.

Werner Heisenberg's discovery of quantum mechanics sprang from the fertile soil of Göttingen and Copenhagen, not Cambridge. Nevertheless, Dirac, knowing only Heisenberg's ground-breaking but rather mysterious and fragmentary paper, produced an almost complete formulation of quantum mechanics wholly on his own, mirroring the achievement of the experienced Göttingen collaboration of Max Born, Pascual Jordan and Heisenberg. Born recalled this as "one of the greatest surprises of my scientific life, for the name of Dirac was completely unknown to me".

Dirac, born 100 years ago this year, often displayed an uncanny ability, whenever the need arose, to invent deep mathematical concepts that were new to physicists. Readers of his early paper would ask by what magic had he turned his austere, abstract constructs into quantitative descriptions of physical phenomena. Dirac's genius was quickly recognized — he was the youngest participant in the élite Solvay Congress of 1927, at which Niels Bohr and Albert Einstein began their long debate about the foundations of quantum mechanics. On first meeting him there, the formidable Wolfgang Pauli quipped that Dirac believed "there is no God, and Dirac is His prophet".

The development of nonrelativistic quantum mechanics — the microscopic counterpart of newtonian mechanics — was essentially complete by the end of 1926. But it was not known how to extend the new theory to the electromagnetic field, or to particles moving with velocities approaching the speed of light. Dirac solved both problems, giving birth to quantum electrodynamics.

Although Dirac's 'quantization' of classical electrodynamics yielded no great surprise, it was the first consistent and correct account of the absorption, emission and scattering of light. Ultimately, all the optical phenomena with which we are so familiar are fully described by Dirac's radiation theory of 1927.

By contrast, Dirac's relativistic wave equation for electrically charged particles, developed the following year, held many surprises — as he later put it, the equation is much more intelligent than its inventor. However one interprets this remark, the invention itself is an unsurpassed example of a disciplined imagination obtaining profound insights into the natural world.

Dirac's equation, when applied to the electron, describes accurately its magnetic moment, and elucidates fine details in the spectrum of hydrogen that are not accounted for by the nonrelativistic theory. Yet the equation seemed to have a terrible flaw, because it also had solutions with negative energy that made no apparent sense. Much effort was devoted to eliminating them, and when that failed, to understanding their significance.

After various inconsistent attempts by himself and others, Dirac made the spectacular proposal that these solutions describe a hitherto unknown particle that has the same mass but the opposite charge to the electron. Furthermore, he predicted that when this 'positron' encounters an electron, the pair would annihilate into two or more photons, and, conversely, that electron–positron pairs could be created by the interaction of energetic photons with matter. Soon after, the positron was discovered in cosmic-ray experiments, and was eventually found to have all the properties predicted by Dirac's theory.

Physics has produced other far-fetched predictions that have subsequently been confirmed by experiment. But Dirac's prediction of antimatter stands alone in being motivated solely by faith in pure theory, without any hint whatever from data, and yet revealing a deep and universal property of nature. The positron illustrates the general principle that all particles that have a conserved attribute, such as charge, have corresponding antiparticles. Furthermore, the existence of antimatter was soon understood to be an inevitable consequence of a

> # Quantum electrodynamics
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> *Paul Dirac's prediction of antimatter stands alone in being motivated solely by faith in pure theory, without any hint whatever from data.*

consistent marriage of relativity with quantum mechanics. A closely related lesson was that the particles that emerge from a reaction need not have existed beforehand — they can be created in the process itself, by the transformation of energy into matter. This fact has become so well established that it is now treated as mundane, but at the outset Dirac's theory was dismissed as incredible by Bohr and other leading figures, even as the evidence for the positron was accumulating.

Quantum electrodynamics has survived more searching experimental scrutiny than any other physical theory. It is valid down to distances more than six orders of magnitude shorter than those that had been explored at the time Dirac invented it. This accomplishment relies on great refinements in mathematical techniques, some of which, such as Richard Feynman's path integral, stem from ideas originating with Dirac. Today, quantum field theory, of which quantum electrodynamics is the prototypical core, is universally considered to be the most successful, fruitful description of the basic constituents of matter and their interactions.

Dirac's creations are a constant presence in today's physics. His abstract, elegant style is now the standard language of quantum mechanics. His maxim that "physical laws should have mathematical beauty" guides throngs of physicists who pursue highly speculative research in the hope that they, too, can discover deep truths his way. The future may confirm another of Dirac's remarkable and brilliant ideas — that magnetic monopoles should exist, as this would explain why all particles carry an electrical charge of an integer multiple of the electronic charge. Indeed, Dirac monopoles, and closely related constructs, loom large in attempts to forge a unified theory of the fundamental interactions. ∎

Kurt Gottfried is in the Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853, USA.

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Truth is beauty: Paul Dirac and the quantum mechanics of the hydrogen molecule.

117

Gigantic Atoms in Space
by Sergei Gulyaev

A student answers an exam question to his professor of physics. He explains that the hydrogen atom consists of an electron orbiting a proton.
"'That's all right", says the professor, "but why does an electron orbit a proton?"
No answer...
"OK, is there anything between an electron and a proton?" professor tries to help the student.
"Oh, yes!"
"What is it?"
"Well, the air, of course!"

Introduction

This student anecdote became almost a reality after the discovery of gigantic atoms, sometimes as big as 0.1 mm, which can have other neutral atoms inside their electron orbitales. A quantum system of macroscopic size? Where could this kind of exotic object exist? The answer is: in the outer space, the best physical laboratory ever known.

Modern astrophysics can be classified both by the *objects of study* and by the *methods of research*:

By objects	By methods
Cosmology	Neutrino astrophysics
Extra-galactic astronomy	Gamma/X-ray astrophysics
Stellar astrophysics	UV astrophysics
Physics of planets	IR astronomy
Physics of the interstellar matter	Radio astronomy

This table is not complete. There also exist astrophotometry, spectroscopy, gravitational wave astrophysics, and they are to be placed in the right-hand column. Physics of comets, and physics of stellar clusters, etc. can be related to the left-hand side. Also, every position in the table can be divided into many sections. For example, stellar astrophysics consists of physics of pulsars, physics of neutron stars, solar physics, etc. At the same time, gamma ray and X-rays astrophysics, plus cosmic rays are usually unified into *high-energy astrophysics*.

One of the greatest achievements of the 20th century astrophysics is the fact that every box in the left-hand side uses all or almost all methods from the right-hand column; and every method from the right-hand column is used in all or almost all sections of astronomy and astrophysics.

In this review we deal mainly with two sections: the interstellar matter (ISM) from the column of objects, and radio astronomy from the column of methods.

70 Years of Radio Astronomy

70 years have passed since the first radio astronomical discovery by Karl Jansky. However, there is no agreement among historians of science about the year when radio astronomy was born. Let us consider the historical facts.

Karl Jansky (1905-1950)

In 1928, Karl Jansky, 23-years old graduate of the University of Wisconsin, joined the Bell Telephone Laboratories in New Jersey. His research work there dealt with the problems of the short wave radiotelephone. Particularly, he was assigned the task of tracking down the crackling static noises that plagued overseas telephone reception. About March 1929, Jansky began the design of a rotatable, directional antenna system and the development of the associated receiver. Construction of the antenna was started in August 1929. It was not until the fall of 1930 that the antenna and its receiving equipment were in good working order. Next came months of prosaic taking of data, that is, data on the characteristics and intensity of radio noises received on 14.6 meters as a function of two variables - (a) time and (b) direction.

In a paper presented in 1932 before the International Scientific Radio Union, Karl Jansky described his equipment and classified the types of static he was receiving into three distinct groups. The first group he described as static from local *thunderstorms*, and the second as static from *thunderstorms* some distance away. Then he stated, "The third group was composed of very steady hiss static the origin of which is not yet known."

In his next paper, entitled "Electrical Disturbances Apparently of Extraterrestrial Origin" (1933), he wrote:

"In conclusion, data have been presented which show the existence of electromagnetic waves in the earth's atmosphere which apparently come from the direction that is fixed in space. The data obtained give for the coordinates of this direction a right ascension of 18 hours and a declination of -10 degrees. The experiments which are the subject of this paper were performed at Holmdel, N.J. (Latitude 40 degrees, 22 minutes North and Longitude 74 degrees, 10 minutes West) during the year 1932."

However, his brother, a radio engineer, wrote: "I remember well, it was 1931, when he started the study of basic principles of astronomy, a field of science in which he had no previous training."

Therefore, we can put the following time frame for this discovery:

1929 - Design of the antenna and the receiving equipment (lambda 14.6 m). Construction begins.
1930 - Observations begin.
1931 - Radio signal from the Milky Way was received. The extraterrestrial nature of the signal was understood.
1932 - The first paper (three types of static radio noises).
1933 - The second paper with the coordinates of the cosmic radio source (the Centre of the Milky Way).

We can see from this analysis that most probably the year 1931 should be considered as the beginning of radio astronomy.

Karl Jansky made his serendipitous discovery while looking for the radio noise of *thunderstorms*. Surprisingly, thunderstorms played crucial role not only in the beginning of

radio astronomy, but also in the invention of radio itself. On May 7, 1895 Alexander Popov first demonstrated a receiver that could detect the electromagnetic waves produced by lightning discharges in the atmosphere many miles away. Each year on May 7, the Soviet Union and now Russia still celebrates "Radio Day" to commemorate the achievements of Alexander Popov.

Alexander Popov
(1859-1905)

On March 24, 1896 Alexander Popov demonstrated transmission and reception of information by wireless telegraphy. The occasion was a meeting of the Russian Physical and Chemical Society and the location was St. Petersburg University. Wireless telegraph signals, transmitted a distance of over 800 feet from another building on the campus, were audible to all in the meeting room. The President of the Society, Professor Petrushevsky, stood at a blackboard holding a paper on which a listing of the letters of the alphabet and their equivalents in Morse Code were written. As the signals were received, Petrushevsky referred to the paper and wrote the appropriate letter on the blackboard. The letters spelled out the name "HEINRICH HERTZ" – the name of a great German physicist who first convincingly demonstrated the existence of the electromagnetic waves predicted in 1864 by James Clerk Maxwell.

Heinrich Hertz
(1857-1894)

Discovery of Gigantic Atoms in Space

Radio astronomy has helped to revolutionise our understanding of the Cosmos. There are two reasons why it became such an important part of astronomy. Firstly, our atmosphere is transparent to radio waves. It means that we can build radio telescopes on the *surface* of the Earth. Secondly, radio astronomy provides a unique opportunity for studying our Galaxy – the Milky Way. Look at the list of greatest discoveries made in radio astronomy:

1. Radio emission from the Centre of the Galaxy   1931
2. 21-cm radio waves from interstellar hydrogen   1951
3. Quasars   1960
4. Molecular maser (OH)   1963
5. Radio recombination lines   1964
6. Cosmic microwave background radiation   1965
7. Pulsars   1967
8. Flat Universe (BOOMERANG Antarctic balloon)   2000
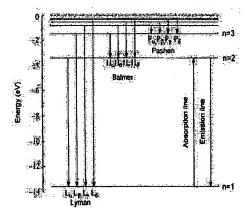
The majority are connected with the study of the Milky Way.

The Galaxy we live in is a flat disk of stars, dust and gas. In visual light we can see not farther around than 2-3 kpc. But the diameter of the Galaxy is about 20-30 kpc. With radio telescopes we can "see" the whole disc throughout. Objects invisible with optical telescopes become accessible to radio observations, including the Centre of the Galaxy - the object first observed as early as in 1931.
One of the most intriguing discoveries of radio astronomy has been that of gigantic atoms in the interstellar space. These are atoms of ordinary chemical elements such as hydrogen, helium and carbon, though in highly "excited" states, which are not found on Earth. These

atoms are called *Rydberg atoms* and they produce features in the spectra of radio sources, known as *radio recombination lines*.

Now, what are Rydberg atoms? Why they are gigantic? Where in space are radio recombination lines formed? Why these spectral lines are "radio" and why are they "recombination"?

Energy levels and transitions in the hydrogen atom

Let us consider the Bohr model of hydrogen atom. The electron travels in circular orbits around the nucleus. The orbits have quantised sizes and energies. They are called atomic energy levels. They are enumerated with numbers ($n = 1$, 2, 3, etc.) called principal quantum numbers. Energy is emitted from the atom when the electron jumps from one orbit to another closer to the nucleus. Transitions from upper levels down to the second level produce quanta of visual light (Balmer line series, 1885). When electron jumps to the first orbit a quantum of ultraviolet radiation is emitted (Lyman line series, 1906). Transitions down to the third level give birth to quanta of IR radiation (Paschen line series, 1908), and so on.

The shorter the arrow in Figure the smaller is the portion of energy emitted as a result of the transition; the smaller the energy the lower the frequency of light emitted.

This relationship between energy levels and frequency of radiation is given by the formula first derived by Rydberg in 1890,

$$ \nu = R\left(\frac{1}{n^2} - \frac{1}{m^2} \right) $$

where $R \approx 3.29 \times 10^{15}$ Hz is the Rydberg constant, n and m are the numbers of the lower and the higher atomic levels.

Historically, Bohr developed his quantum theory of atom (1913) on the base of experimental works of Balmer, Lyman and Paschen. Bohr's theory explained the observed series as transitions to the first three atomic levels ($n = 1, 2, 3$) and it predicted new lines. The theory, however, gave no indication of how many series could be detected in practice. Progress of experimental studies towards the longer wavelengths was very slow. The fourth series, the Bracket series ($n = 4$) was detected nine years after Bohr's theory had appeared; the fifth (Pfundt, $n = 5$) after 11 years; and the sixth (Humphfrey, $n = 6$) only after 40 years, in 1953.

With these measurements classical laboratory spectroscopy ran out of abilities. But why? What prevented us from finding atoms with higher quantum numbers? Here we should pay attention to another important property of the Bohr's atom – its size. According to quantum mechanics the diameter of the atom increases with the quantum number n of the electron's orbit as

$$ d_n = n^2 \times 10^{-7} \text{ millimetre} $$
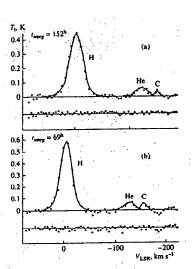
It means that when the atom is in the ground state ($n = 1$) its size is about 10^{-7} mm, but when $n = 10$ the atom becomes 100 times bigger. Such a huge atom cannot exist in ordinary

4

laboratory conditions. Even if we find a way to create it, it will be immediately destroyed by impacts with other particles. Laboratory medium, even rarefied, even the so-called laboratory vacuum is too dense for gigantic atoms to survive! Cosmos, namely the interstellar matter, is empty enough to be an ideal place for gigantic atoms to exist.

In the ionised gas an electron and an ion may pass close enough to each other that, with a suitable release of energy, they become bound, with the electron in an energy level having a large principal quantum number. Most of these newly bound electrons immediately jump to the ground state, releasing energy in the UV emission lines of the Lyman series. In a few cases the electrons cascade downwards from level to level, releasing their energy in a series of lines known as *recombination lines*. In 1959, Nikolai Kardashev suggested that these lines might be detectable at radio wavelength.

22-m radio telescope (RT-22) in Puschino

In 1964, the first radio recombination line was detected with the help of 22-m radio telescope of Lebedev Physical Institute in Puschino (Russia). It was H90-alpha line in the Omega Nebula. The letter H means hydrogen, the number 90 means $n = 90$, the Greek letter alpha means $(m - n) = 1$. In other words the transition between levels 91 and 90 in the atom of hydrogen was detected. What a giant leap after the last laboratory achievement of Humphfrey (transition 7 – 6)!

Next few years best radio observatories in the world were involved in the search of radio recombination lines. Discoveries followed one by one: H104-alpha (Pulkovo), H109-alpha (NRAO), H156-alpha (Parkes), H253-alpha (Bonn). In 1966 first radio recombination lines of helium (He156-alpha) and carbon (C109-alpha) were detected in galactic nebulae.
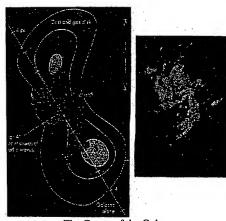
It is possible to observe lines of hydrogen, helium and carbon separately because the Rydberg constant is a function of mass:

$$R = R_\infty (1 - \frac{m_e}{M_a})$$

where m_e is the mass of electron, M_a the total mass of the atom, and R_∞ the constant for infinite mass. The spectra of the H, He, and C radio recombination lines of the 56-alpha (a) and 57-alpha (b) transitions obtained with RT-22 in the nebula W3A are shown in figure.

Spectra of the H, He, and C radio lines

Radio Recombination Lines and Study of the ISM

Astrophysically, radio recombination lines are very important. The ratio of the energy radiated in the line to that of the underlying continuum is a measure of the gas temperature.

The Centre of the Galaxy
in the H109-alpha radio recombination line

The line width gives the measure of the gas density. In addition, the Doppler shift of a spectral line in the spectrum gives information about the velocity fields of the gas.

The last and probably most important thing to know is that *velocity means location*. (Sounds like *"time is money."*) Yes, knowing the velocity of a galactic object gives us an opportunity to locate this object in the galactic disc. In short, radio lines allow us to create a map of the Milky Way galaxy.

It often happens in science: something that seemed to be just nonsence or a vexing obstacle, becomes a very important element of the scientific picture of the world. The ISM is almost nothing; its density is many orders of magnitude less than the density of the deepest vacuum ever created in the physical laboratory. But as we now know, the ISM is the mutual element of the stellar life cycle. The interstellar medium is the matrix within which the processes of galaxy evolution occur. It exists in many states: atomic and ionised hydrogen, relativistic plasma, molecular gas, and dust, each containing velocity and density structures over a vast range of scales.
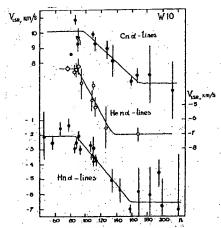
Radio recombination lines is an ideal tool for studying the ISM. New, more accurate characteristics of the components of the ISM were obtained. Great progress was achieved in the physics of galactic nebulae – HII-regions. Complex theoretical models of gaseous nebulae were created. We first clearly understood that the nebulae were inhomogeneous. That they have a core and a less dense envelope, and that the matter of the core consists of many clumps. Now it is confirmed by brilliant observations with HST and VLT (see the article "The Orion Nebula – the Jewel of the Sword" in the December 2000 issue of the AAS Journal).
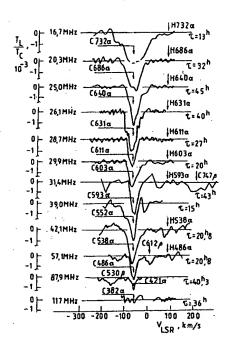
Look at a beautiful picture of a planetary nebula. We can see an envelope of the ionised gas, expanding out from the central star of the planetary nebula – the white dwarf. The last page in the scenarium of evolution of our Sun. Diffuse nebulae are expanding too. When new stars are born in a dense cold molecular cloud they begin to ionise matter around them. They change the cold gas into hot plasma. Gas pressure becomes 1000 times higher than that in the surrounding cold gas. The hot inner area expands until it reaches the edge of the cloud. Plasma, fire comes out of the cloud like champaign out of the bottle when you open it. A beautiful nebula becomes visible...

Expansion, everywhere expansion. We got accustomed to this theoretical scenarium so much that a simple question takes us unawares. The question is: how to prove that pictures of nebulae we can see testifies to the expansion, not collapse? Well, we can take a picture of a nebula today, wait for 20 years, then take another shot and compare the two photographs. Unfortunately this plan is not real. A diffuse object has no sharp edges to compare.

Radio recombination lines proved expansion of nebulae elegantly. The Doppler shift of a spectral line in the spectrum of an object gives us the velocity of the object with respect to us. So we can measure the relative velocity of a nebula. Nebulae are opaque to radio waves in low frequencies. So, in low frequensies we can see nothing but the closest part of the nebula,

6

This graph demonstrates the expansion, not collapse of the nebula. Shows the radial velocity as a function of the principal quantum number for the Orion Nebula (W10).

Spectra of radio recombination lines with the highest transitions observed. Frequency and integration time are indicated for each line. Arrows show the computed positions of the lines of carbon and hydrogen.

and the velocity we measure from the shift of the line tells us about the outer, closest to us layer of the nebula. At the same time nebulae are transparent to radio waves with high frequencies. It means that the Doppler shift of a corresponding radio line tells us about the velocity integrated over the whole body of the nebula. This integrated velocity is the velocity of the nebula centre. If the difference between velocity of the nebula centre (high frequency) and the closest edge of the nebula (low frequency) is positive, the nebula is expanding. The negative difference would tell us about the collaps, but it has never happened yet.

A new period of research in radio recombination lines came with a discovery made in Charkov (Ukraina) with the help of the decametric radio telescope. Konovalenko and Sodin (1980) reported the detection of a weak absorption line at 26.13 MHz in the nonthermal emission from the Cassiopeia supernova remnant, which proved to be the 631-alpha recombination line of carbon. During the eighties, the spectral range of the investigation of radio recombination lines expanded rapidly into the long-wavelength region. Spectral lines up to C732-alpha were observed towards Cas A. If we now apply the formula for the atomic size, we see that the size of the atom should be about 0.1 mm!

The observation of low-frequency lines of carbon was a considerable surprise which besides its attraction caused several questions: 1. Why is it possible to observe the lines of carbon with $n > 400$, while lines of the most abundant element of the ISM – hydrogen – are absent? 2. What is the highest possible level n, and what determines this limit?

The analysis carried out showed that for the formation of radio lines with $n > 400$ it is necessary that the interstellar cloud has a low electron density and is sufficiently cold. In the ISM both conditions are fulfilled at large distances from hot stars, where all hydrogen is neutral (i.e., non-ionised). It means that these lines can not be formed in the Cas A radio source. They arise somewhere between Cas A and the Earth in a cold interstellar gas. It makes them a very important probe for the physical conditions in cold interstellar clouds.
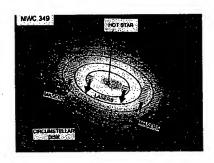
7

There is no final answer to the second question yet. Today we believe that atoms can hardly exist in states higher than $n = 1000$. The more accurate statement should sound like: the probability for the electron to occupy the atomic level with $n > 1000$ is negligeble. Perturbations from plasma particles, cosmic rays, and even from the microwave background radiation effectively destroy "super-gigantic" atoms.

The First Natural Laser in Space

Probably the most exciting discovery of recent years was that of the first natural laser in space. It was detected by scientists on board of the Kuiper Airborne Observatory (KAO) as they trained the aircraft's IR telescope on a young, very hot, luminous star in the constellation Cygnus. The laser was detected at 169 microns on the edge of the gas and dust disk surrounding MWC 349.

A laser (light amplification by stimulated emission of radiation) works on the principle of pumping atoms to high energy states, then allowing a photon of similar wavelength to cause a cascade of downward transitions and a focused emission of many photons. The laser is created when an intense ultraviolet light from a star "pumps" or excites hydrogen atoms in the gaseous, dusty disk surrounding the star. Then, when the IR light shines on the excited hydrogen atoms, it causes the atoms to emit an intense beam of light at exactly the same wavelength, creating the circumstellar laser.

Circumstellar disc surrounding the hot star MWC349. Maser emission thought to occur in outer regions while lasers are operating near the central star.

The "lasing line" in MWC 349 is the recombination line H26-alpha. Its intensity is six times brighter than non-amplified spontaneous emissions at the same wavelength. Discovery of this naturally occurring laser provides us with a powerful tool for probing the conditions in disks of gas and dust surrounding young stars. Many of these circumstellar disks are regions where planets are forming.

Conclusion

We cannot discuss in a short article all aspects of the problem called Gigantic Atoms in Space. Since 1964 this topic has spread widely and penetrated into many different branches of physics and astrophysics. Radio recombination lines have become the most reliable method in cosmology for measuring the primordial (created in the first three minutes) abundance of helium. Whole branches of quantum physics and spectroscopy, such as the spectral line broadening theory and atomic level population theory were tested and challenged by the observations of radio recombination lines. Fundamental question about the biggest possible atom that can exist in nature was stimulated by this research. Planetary and diffuse nebulae, cold interstellar clouds and circumstellar discs, our Galaxy and its structure are among the objects of study...

Everything is interconnected in science. You begin to work in one field of science and unavoidably impact many related problems from its other branches. This is the character of science itself. And this is what makes it so exciting!

SEH-2 Latest Solar EUV Measurements

END OF MISSION REPORT

8/18/97

Submitted by: Darrell L. Judge. P-I

Animated Spectral Sunrise!
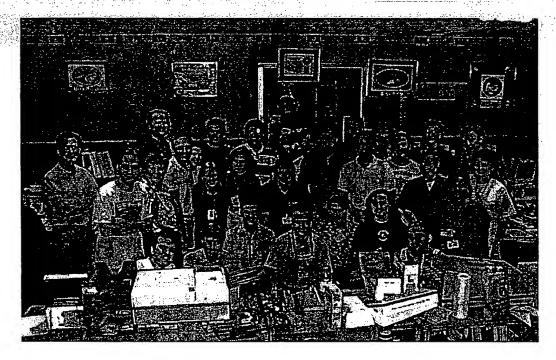
The SEH extreme ultraviolet instrumentation aboard the space Shuttle Discovery (STS-85) has produced excellent full disk absolute solar flux data throughout the mission. All our primary objectives were met or exceeded. The observations consisted of thirteen subsolar data sets, In addition to three at sunset, one at sunrise and one data set running from sunrise through sunset.

The SEH instrumentation consists of :

1. A Ti coated Si photodiode plus an Al free standing film for observing the full solar disk shortward of 200 A (Angstroms).

2. An Al coated Si photodiode plus an Al free standing film located on the GLO 6 scan platform, to observe the full solar disk In the wavelength region shortwards of 800 A.

3. A helium double ionization cell measuring the photoionization rate of helium.

4. A neon ionization cell which measures the absolute solar flux at wavelengths shortward of 575 A.

5. A normal incidence vacuum ultraviolet spectrometer which measures the solar spectrum from 250 -1700 A.
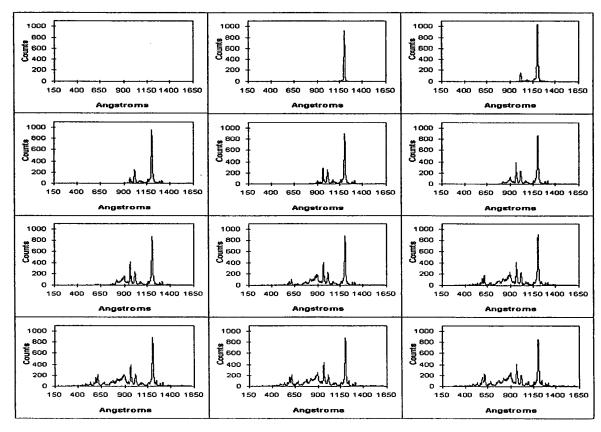
Examples of the raw data obtained in real time during the flight are given in the following figures.

Part of the IEH/TAS mission operations team.

The power of spectrally resolved planetary atmosphere occultation data may be seen in the real time spectra obtained during Shuttle sunrise, August 11, 1997. A sequence of twelve spectra showing the altitude dependence of the atmospheric column density in the Earth's upper atmosphere is shown in Figure 1. This same technique can be readily applied to the atmosphere of Pluto, for example, to measure atmospheric composition and temperature. Such data can be realistically obtained using low weight and low power instrumentation meeting the resources likely to be available for a Pluto mission, unlike airglow observations.
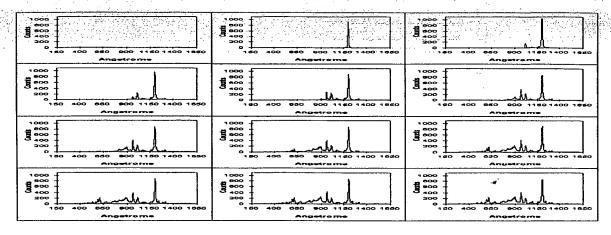
Figure 1. A sequence of spectra showing the altitude dependence of the atmospheric column density in the wavelength range shortward of 1600 A.

The dynamic nature of the solar flux in the extreme ultraviolet (EUV) can be seen in Figure 2. During the eleven day mission the flux shortward of 200 A changed by more than 30%! IT is clear from such data that atmospheric observations should be accompanied by simultaneous observations of the EUV which is driving much of the photochemistry of planetary atmospheres. The observed variability is consistent with that observed in the EUV region being continuously monitored by our CELIAS/SEM instrument on SOHO.
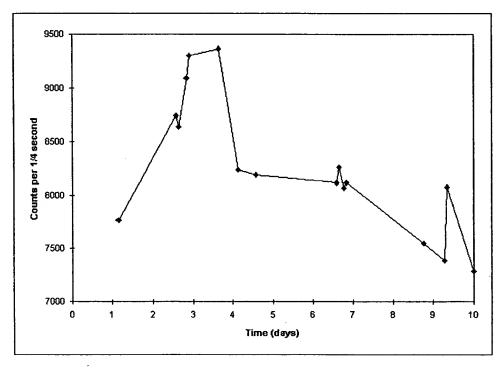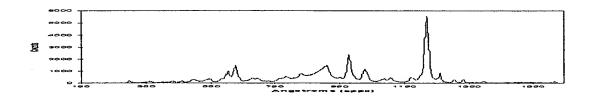
Figure 2. The full disk solar flux in the spectral region shortward of 200 A. Changes in flux greater than 10% are seen to occur in a matter of hours.
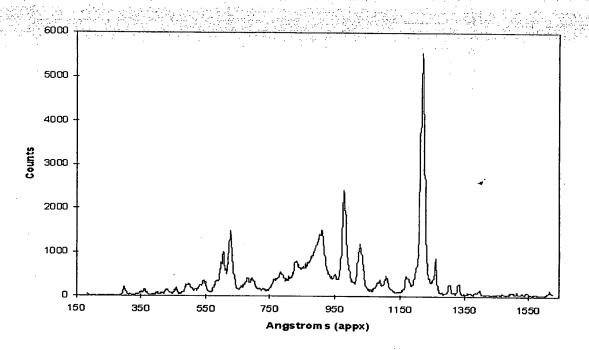
Figure 3. Raw Solar EUV Intensity Spectrum without a spectral filter. The large peak is HI Lyman-α at 1216 A. The small peak left of 350 A is the He II 304 A emission.
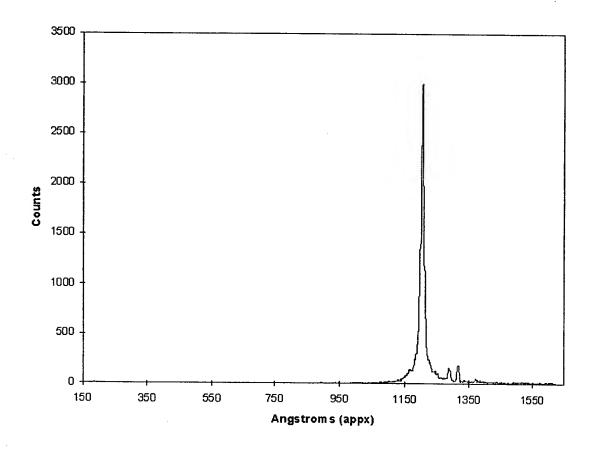
Figure 4. Raw Solar EUV Intensity Spectrum observed through a MgF filter. The dominant feature shown is the HI Lyman-α resonance emission.
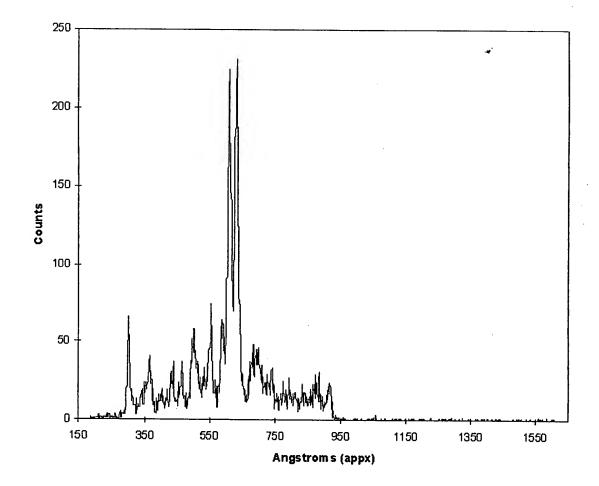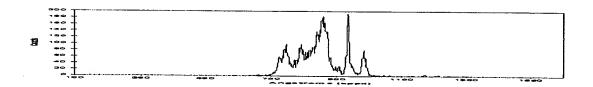
Figure 5. Raw Solar EUV Intensity Spectrum with an Al filter. The nominal Al band-pass is between 170 to about 800 A. Radiation counts longward of 800 A are due to multiple order photons. The sharp cutoff near 950 A is due to physical blockage of the incident radiation by the Al filter mount. Emissions due to helium and oxygen are evident in the spectral region near 550 A. The far left peak is the intense He II (304 A) resonance emission.
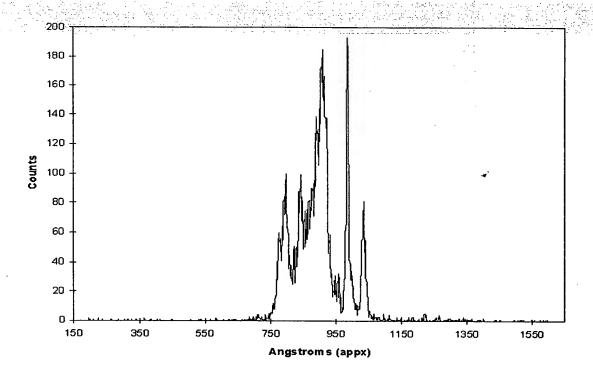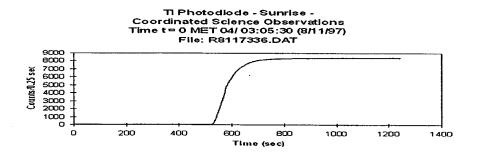
Figure 6. Raw Solar EUV Intensity Spectrum as observed through an Indium Filter. The nominal wavelength band-pass is between 750 and 1100 A. The two lines on the long wavelength side of the spectrum are the CIII (977 A) and HI Lyman-β (1025 A) emissions. Also shown is the hydrogen continuum beginning at the ionization limit at 911 A.

August 11, 1997 Sunrise/Sunset - Coordinated Science Observations

STS-85 Shuttle Mission, Orbit 67

Simultaneous solar EUV irradiance data were obtained by the IEH/SEH Shuttle instrumentation on Discovery and by the USC sounding rocket instrumentation launched from the White Sands Missile Range (WSMR) at MET 04/03:37 simultaneous measurements were obtained for about 10 min. The coordinated SEH observations were successfully performed on August 11, 1997 between MET 04/03:06 and MET 04/04:04. The SEH and the sounding rocket measurements provided a set of complementary data. Examples of the spectral data obtained by the SEH spectrometer during the mission are shown in the preceeding figures. The following two figures show the integrated solar soft X-ray flux shortward of about 200 A, corresponding to the use of a Ti coated photodiode plus a free standing Al filter.

Ti Photodiode - Sunrise -
Coordinated Science Observations
Time t = 0 MET 04/03:05:30 (8/11/97)
File: R8117336.DAT
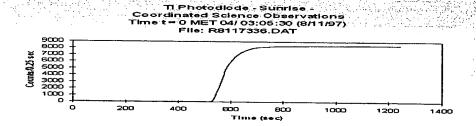
Figure 7. Ti coated Si photodiode data obtained during the sunrise solar occultation on August 11, 1997.
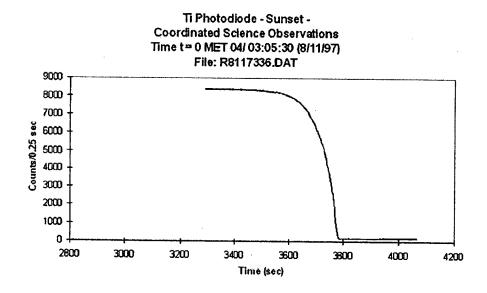
Figure 8. Ti coated Si photodiode data obtained during the sunset solar occultation on August 11, 1997.

Back to Space Sciences Center Menu

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⌐ *University of Southern California*

ATOMS AND MOLECULES

An Introduction for Students of Physical Chemistry

MARTIN KARPLUS
Harvard University

RICHARD N. PORTER
State University of New York
at Stony Brook

**ATOMS AND MOLECULES An Introduction for
Students of Physical Chemistry**

nto the answers to these questions, we follow a
hat is, we sketch the experimental and theoreti-
owledge of the elementary particles and their
resent understanding to modify the purely his-
us to capture the spirit of the new discoveries,
blind alleys into which the early investigators

M

st half of the nineteenth century, a period of
ment of chemical theory. Because the concept
by Dalton to be of fundamental importance
hemical combination, chemists generally be-
basic constituents of matter and that if one
the atoms, regarded as elementary particles,
hing about chemistry.
ved that the laws of motion for atoms were
een firmly established by Newton for astro-
ws of motion of everyday mechanics. Since
blocks of all matter, the nineteenth century
henomena (including chemistry and biology,
ome of horse races and political crises) could
ifferential and integral calculus.
inistic view is brought out by some simple
isolated particle which has a certain mass, a
velocity at some initial time, it is possible
edict its position and velocity exactly for all

ı velocity v directed along the x axis. If it
: $t = 0$, and there are no forces, then accord-
locity remains constant and the position at
$\prime_0, z_0)$.
le (initially moving in the x direction with
ne or more other particles, and that these
nother. If the x component of the force on
ond law tells us that the velocity of the
rate proportional to the force,

$$\frac{dv}{dt} \propto F$$

stant can be taken to be the reciprocal of
is, we can write

$$F = ma \tag{1.1}$$

where

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

is the acceleration. If we know how the force F depends upon the position
of the particles, then we can integrate Eq. 1.1 to obtain the position and
velocity of the particle of interest at any future time. We could then
proceed, in principle, to solve Newton's equations simultaneously for all the
particles in the system and thereby obtain a complete knowledge of its
future behavior.

The two classical ideas—that atoms are the fundamental particles and
that the motion of these fundamental particles is governed by Newton's
laws—thus lead to a clear, simple, and well-defined picture of nature. As
we know now, these classical hypotheses are both wrong. There are particles
more elementary than atoms—namely, electrons and nuclei—which de-
termine chemical phenomena. (We are considering here phenomena ex-
ternal to the nucleus, so that we need not be concerned with the details of
nuclear structure.) Furthermore, electrons have such a small mass (on the
order of 10^{-27} g) and their velocities can vary so rapidly over short distances
[dv/dx is on the order of 10^{16} (cm/sec)/cm for electrons in atoms and mole-
cules, or about 10^{13} times the corresponding value for an object falling
slowly in the earth's gravitational field] that the extention of Newton's
laws from macroscopic bodies to this microscopic realm cannot be taken
for granted. In fact, Newton's laws do not apply to electrons in atoms,
and a set of laws, comprising what is known as quantum mechanics,
has to be obtained for a correct description of electronic behavior. New-
ton's laws, which are adequate for macroscopic objects (moving with ve-
locities small compared with the speed of light), turn out to be a special
case to which the equations of quantum mechanics reduce when the mass
of the object becomes large and the force upon it varies slowly with posi-
tion.

1.2 THE ELECTRON

The concept of the electron as a particle had its modern origin in Fara-
day's experiments with electrolytic cells. He discovered that the amount of
a substance chemically liberated at an electrode was proportional to the
amount of electricity passed through the cell. Furthermore, if several
different cells were placed in series, a given quantity of electricity liberated
chemically equivalent amounts of the various substances. Faraday's in-
terpretation of these results was that equivalent weights of substances
(1 g of hydrogen, 108 g of silver, 8 g of oxygen, and so on) contained equal

one can choose the b; and a so that $\psi_n(r)$ satisfies the equation for all values of r, if the energy E has a certain value E_n that depends on the principle quantum number n. For $n = 1$ and $n = 2$, we have seen that $E_1 = -Z^2e^2/2a_0$ and $E_2 = -\frac{1}{4}Z^2e^2/2a_0$, respectively. In the general case, it can be shown that

$$E_n = -\frac{1}{n^2}\frac{Z^2e^2}{2a_0} \qquad n = 1, 2, 3, \ldots \qquad (3.35)$$

Comparison of Eqs. 3.35 and 1.57 demonstrates that for spherically symmetric states of the hydrogen atom, the energy levels (and therefore the Rydberg constant) predicted by the Bohr model and the quantum theory are identical. The spherically symmetric wave functions are discussed further below (see Section 3.10).

3.6 FUNCTIONS WITHOUT SPHERICAL SYMMETRY

Let us now look at the hydrogen-atom states in which the wave function is not spherically symmetric. The wave function is of the general form given in Eq. 3.9 and satisfies the complete Schrödinger equation (Eq. 3.9). The possibility now arises for nodes in the angular functions $\Theta(\theta)$ and $\Phi(\phi)$, since they are no longer constant for states that are not spherically symmetric. As the simplest functions of this type, we consider those with one angular node. They have the form $x f(r)$, $y f(r)$, $z f(r)$ or $r \sin\theta \cos\phi f(r)$, $r \sin\theta \sin\phi f(r)$, $r \cos\theta f(r)$, with $f(r)$ to be determined by substitution into the Schrödinger equation. These three functions are equivalent except for their orientation, and each has one angular node; for example, for any value of r, the function $z f(r)$ is zero for $\cos\theta = 0$ (i.e., $\theta = \pi/2$).

To see if these functions satisfy the Schrödinger equation, we substitute them into Eq. 3.9. Considering $x f(r) = r \sin\theta \cos\phi f(r)$ as an example, we have for the angular derivatives,

$$\frac{\partial^2[r\sin\theta\cos\phi f(r)]}{\partial\phi^2} = r\sin\theta f(r)\frac{\partial^2(\cos\phi)}{\partial\phi^2}$$
$$= -r\sin\theta\cos\phi f(r)$$

and

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta}[r\sin\theta\cos\phi f(r)]$$
$$= r\cos\phi f(r)\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\sin\theta}{\partial\theta}\right)$$
$$= r\cos\phi f(r)\left(\frac{\cos^2\theta - \sin^2\theta}{\sin\theta}\right)$$

The radial derivative is

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\left[r\sin\theta\cos\phi f(r)\right]\right)$$
$$= \sin\theta\cos\phi\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\left[rf(r)\right]\right)$$
$$= \sin\theta\cos\phi\left(r\frac{d^2f}{dr^2} + 4\frac{df}{dr} + \frac{2}{r}f(r)\right)$$

Introducing these results into Eq. 3.9, we obtain

$$\sin\theta\cos\phi\left(r\frac{d^2f}{dr^2} + 4\frac{df}{dr} + \frac{2}{r}f(r) + \frac{\cos^2\theta - \sin^2\theta}{r^2\sin^2\theta}f(r)\right.$$
$$\left. - \frac{1}{r^2\sin^2\theta}f(r)\right) - \frac{Ze^2}{r}f(r) = Ef(r) \qquad (3.36)$$

where we have divided[3] both sides by $r\sin\theta\cos\phi$. Combining the angular terms, we see that they cancel the term $(2/r^2)f(r)$, so that Eq. 3.36 reduces to the radial equation

$$-\frac{\hbar^2}{2m}\left(\frac{d^2f}{dr^2} + \frac{4}{r}\frac{df}{dr}\right) - \frac{Ze^2}{r}f(r) = Ef(r) \qquad (3.37)$$

The identical equation is obtained from the function $y f(r)$ and $z f(r)$, verifying the assumption that the radial part $f(r)$ is the same for all three functions (see Problem 3.6). The form of Eq. 3.37 is very similar to the previous radial equation (Eq. 3.13), the only difference being that the factor $2/r$ in front of the first-derivative term is now $4/r$. This suggests that we try the same exponential-times-polynomial form for $f(r)$ as was used for $R(r)$. Furthermore, since we are interested in the lowest state with one angular node, we assume a simple nodeless exponential; that is, $f(r) = e^{-ar}$ with a to be determined from Eq. 3.37. The result of setting the coefficient of each power of r equal to zero is

$$a = \frac{Z}{2a_0} \qquad E = -\frac{1}{4}\frac{Z^2e^2}{2a_0}$$

Evaluation of the normalization constant yields

[3] Strictly speaking, one can divide by $r\sin\theta\cos\phi$ only if θ and ϕ have values for which $\sin\theta\cos\phi \neq 0$. Thus, for $\theta = 0$, π or for $\phi = \pi/2$, $3\pi/2$, Eq. 3.9 is satisfied by any function $f(r)$, while for all values of θ and ϕ other than these, $f(r)$ must satisfy Eq. 3.37. The requirement that the wave function be continuous (otherwise, there would be unacceptable discontinuities in the probability density) means that $f(r)$ must satisfy Eq. 3.37 for all values of θ and ϕ. The result is therefore the same as if we divide both sides of the Schrödinger equation by $r\sin\theta\cos\phi$, without regard to the values of θ and ϕ.

$$\psi_x = \frac{1}{4}\left(\frac{Z^5}{2\pi a_0^5}\right)^{1/2} r \sin\theta \cos\phi \exp\left(-\frac{Z r}{2a_0}\right)$$

$$\psi_y = \frac{1}{4}\left(\frac{Z^5}{2\pi a_0^5}\right)^{1/2} r \sin\theta \sin\phi \exp\left(-\frac{Z r}{2a_0}\right)$$

$$\psi_z = \frac{1}{4}\left(\frac{Z^5}{2\pi a_0^5}\right)^{1/2} r \cos\theta \exp\left(-\frac{Z r}{2a_0}\right)$$

Thus, the three simplest angular functions all have the same energy, which is also equal to the energy of ψ_2, the second spherically symmetric solution. This is another example of degeneracy for a three-dimensional system with spatial symmetry, analogous to that of the cubic-box problem. In the hydrogen atom, the symmetry is provided by the spherically symmetric potential, which requires that solutions differing only in their spatial orientation—as do ψ_x, ψ_y, ψ_z—must have the same energy. That the spherically symmetric function ψ_2 has the same energy as the angle-dependent functions ψ_x, ψ_y, ψ_z is not due to simple spatial symmetry; instead it is a consequence of the Coulomb interaction between the electron and the nucleus. In the discussion of many-electron atoms (Chapter 4) we shall see an example of a non-Coulombic interaction for which this degeneracy is not present.

Additional nonspherically symmetric functions can be found by using the same angular dependence as above and introducing one or more radial nodes. Alternatively, the number of angular nodes can be increased; for example, functions such as $xy\,g(r)$, $xz\,g(r)$ can be introduced and $g(r)$ determined so as to satisfy the Schrödinger equation. Rather than continuing with such a step-by-step procedure for generating the radial and angular hydrogen-atom solutions, we proceed to describe some of their properties. Further details concerning the general method of solution of the Schrödinger equation can be found in texts on quantum mechanics (see, for example, References 2 and 3 in the Additional Reading list).

3.7 QUANTUM NUMBERS FOR HYDROGEN-LIKE ATOMS

For hydrogen-like atoms, three quantum numbers are required to completely specify the state or wave function. These three quantum numbers are analogous to the quantum numbers n_x, n_y, n_z, appearing in the cubic-box problem, although the use of spherical polar coordinates for the atomic case means that the three quantum numbers play a somewhat different role. In the discussion of spherically symmetric hydrogen-like functions, we introduced the principal quantum number n, which determined the energy

$$E_n = -\frac{1}{n^2}\left(\frac{Z^2 e^2}{2a_0}\right)$$ (3.38)

and the number $(n-1)$ of radial nodes. For the nonspherical functions ψ_x, ψ_y, ψ_z, each of which had one angular node, we found that the energy was the same as for ψ_2 with one radial node. This suggests (it turns out to be a correct suggestion) that the principal quantum number n applies to all of the hydrogen-atom solutions; it specifies their energy, according to Eq. 3.38, and gives the total number of nodes, both radial and angular, as $n-1$.

A second quantum number for the hydrogen atom is designated by the letter l and it specifies the number of angular nodes. It is often called the azimuthal quantum number. Since the total number of nodes, both radial and angular, is $n-1$, the allowed values of l are

$$l = 0, 1, 2, \ldots, n-1.$$ (3.39)

that is, the number of angular nodes must be less than or equal to the total number of nodes. There are thus l angular nodes and $n-l-1$ radial nodes. The spherically symmetric functions discussed previously (ψ_1 and ψ_2) have $l = 0$ (no angular nodes) and $n = 1$ and 2, corresponding to zero and one radial node, respectively. The functions ψ_x, ψ_y, ψ_z all have $n = 2$ and $l = 1$; that is, they have one angular node and zero radial nodes.

An important aspect of the azimuthal quantum number is that it specifies the magnitude squared, M^2, of the angular momentum of the electron in the atom. Just as the energy increases with the number of nodes of the wave function ψ, so the angular momentum increases with the number of nodes in the angular part of the wave function $\Theta\Phi$. Quantitatively, the result is that

$$M^2 = l(l+1)\hbar^2 \qquad l = 0, 1, 2, \ldots, n-1$$ (3.40)

The electronic angular momentum of the hydrogen atom is seen to be quantized in the new quantum theory as well as in the Bohr model, although the allowed values of M are no longer integral multiples of $\hbar$ (compare Eq. 1.54). It will be recalled that in the Bohr theory the motion of the electron was planar, so that the angular momentum was a number (scalar). In the quantum-theory treatment, however, planar motion is not allowed. If the electron were confined to a plane, say, the xy plane, the z components of the position coordinate and the velocity would be exactly zero. Thus, the uncertainties Δz and Δp_z would be both zero, in clear violation of the uncertainty principle. For nonplanar motion, the angular momentum is a vector with components M_x, M_y, M_z. By an appropriate choice of axes, M_z can be made to coincide with the angular momentum (p_ϕ) for the planar motion of the Bohr theory. We expect the same quantization rules to apply to M_z and p_ϕ. This is true in that M_z is given by the expression

$$M_z = m\hbar$$ (3.41)

where the quantum number m is a positive or negative integer or zero. The sign of m determines whether the z component of angular momentum points in the positive or negative z direction. In contrast to the Bohr-theory rule for p_ϕ, however, the quantum number m is distinct from the principal quantum number n. As we shall see later, m may be measured by observing the spectrum of the atom in a magnetic field; for this reason, m is called the *magnetic quantum number*. Since M_z is one component of the angular momentum M, the absolute value of M_z cannot exceed M; that is, the inequality $|m| \le [l(l+1)]^{1/2}$ must hold. With the additional requirement that both m and l are integers, the allowed values of m are seen to be

$$m = 0, \pm1, \pm2, \ldots, \pm l \tag{3.42}$$

Specified in this way, the absolute value of the quantum number m, that is, $|m|$, turns out to be the number of nodal planes of $\psi(r, \theta, \phi)$ that are perpendicular to the xy plane.

Summarizing the above discussion, we conclude that the quantum numbers n, l, and m specify the hydrogen-atom wave functions, with allowed values

$$n = 1, 2, 3, 4, \ldots$$
$$l = 0, 1, 2, 3, \ldots, n-1$$
$$m = 0, \pm1, \pm2, \pm3, \ldots, \pm l$$

The principal quantum number n determines the total energy,

$$E_n = -\frac{1}{n^2}\left(\frac{Z^2e^2}{2a_0}\right)$$

the azimuthal quantum number l determines the square of the total angular momentum

$$M^2 = l(l+1)\hbar^2$$

and the magnetic quantum number m determines the z component of the angular momentum

$$M_z = m\hbar$$

Since the energy of the hydrogen atom is given by Eq. 3.35, states with different l and m but with the same n are degenerate. For a given n, Eq. 3.42 shows that there are n different possible values of l. In turn, for each value of l, Eq. 3.42 shows that $2l + 1$ different values of m are possible. The total number of states with the same energy (that is, the degeneracy) is

$$g = \sum_{l=0}^{n-1}(2l+1) = 1 + 3 + 5 + \cdots + 2n - 1 = \frac{(1 + 2n - 1)n}{2} = n^2 \tag{3.43}$$

It should be emphasized again that this n^2-fold degeneracy for the hydrogen atom or hydrogen-like atoms is due to the fact that $V(r) = -Ze^2/r$. A change in the form of the potential energy to a non-Coulombic interaction makes the energy depend on both n and l. If in addition the spherical symmetry of the potential is removed by applying an external magnetic field, the energy depends on m as well.

3.8 WAVE FUNCTIONS FOR ONE-ELECTRON ATOMS

In terms of the quantum numbers n, l, and m, the wave functions for a one-electron atom with nuclear charge Ze can be specified as

$$\psi_{nlm}(r, \theta, \phi) = R_{nl}(r)\,\Theta_{lm}(\theta)\,\Phi_m(\phi) \tag{3.44}$$

Here the quantum numbers associated with each of the factors R, Θ, and Φ are the ones required to determine the form of that function uniquely. Table 3.1 lists the quantum numbers and the corresponding functions of all the states ψ_{nlm} with $n = 1$, 2, and 3. The first five functions in the table are the ones that we have considered above. Comparison of the functions in Table 3.1 for various n, l, m shows that the R factors depend on both n and l, that the Θ factors depend on l and m, and that the Φ factors depend on m alone.

The wave functions given in Table 3.1 are all normalized; that is,

$$\iiint_{\text{all space}} \psi_{nlm}^2 (r, \theta, \phi)\, r^2\, dr \sin\theta\, d\theta\, d\phi = 1 \tag{3.45}$$

the required normalization constants being given at the bottom of the table. Another property of the functions in the table is that they are *orthogonal*; that is,

$$\iiint_{\text{all space}} \psi_{nlm}\psi_{n'l'm'}\, r^2\, dr \sin\theta\, d\theta\, d\phi = 0$$

for one or more of the quantum numbers $n'l'm'$ not equal to nlm; that is, the integral in Eq. 3.45 is zero for two hydrogen-atom wave functions as long as the two functions are different. The orthogonality of different wave functions in quantum mechanics is a general property. The term "orthogonal" is used in analogy to the orthogonality of two vectors a, b which point at 90° so that their scalar product $(a_xb_x + a_yb_y + a_zb_z)$ is zero. To illustrate the orthogonality, we consider the integral

$$\iiint_{\text{all space}} \psi_{100}(r, \theta, \phi)\psi_{210}(r, \theta, \phi)\, r^2\, dr \sin\theta\, d\theta\, d\phi$$
$$= N_1N_2 \int_0^\infty \exp\left(-\frac{Zr}{a_0}\right)\frac{Zr}{a_0}\exp\left(-\frac{Zr}{2a_0}\right) r^2\, dr \int_0^\pi \cos\theta \sin\theta\, d\theta \int_0^{2\pi} d\phi$$

Kline-Anderson, Inc.

ORIGINAL

Review of Schedule and Resource Requirements to Develop a HydroCatalysis Functional Prototype Unit

Final Report for
Technology Insights

October 23, 1996

8926 Kirby Drive, Houston, Texas 77054
713-660-8414   Fax: 713-665-5934

Copy __2__ of __8__ ;   Assigned to __BLACKLIGHT POWER__

Apparently there is color, apparently sweetness, apparently bitterness;
actually there are only atoms and the void.

Democritus 420 BC

Table of Contents

Attachment A
Commitment to Commercialization Investment
Phases I - IV.   (Technology Insights)

Attachment B
HydroCatalysis Project Phase I Schedule dated 9/24/96. (Technology Insights)

Attachment C
Definition of Phase I Test Cell Milestones (Technology Insights, assisted by
Kline-Anderson).

Attachment D
List of Documents received by Kline-Anderson Inc. as background material from
HPC and Technology Insights.

Attachment E
"Conceptual characterization of HydroCatalysis Turbine Application Options"
(Technology Insights).

Attachment F
"S-1 Radiant Recirculating Boiler" (Technology Insights).

1. Introduction

Objective:

The scope of work for this technical evaluation contract consists of the following:

"Review the current status of the HydroCatalysis process development and plans for development of the functional prototype unit, and provide comments and recommendations regarding the planned tasks, resource requirements and projected schedule."

The subtasks for completing the review were broken down into four areas, that are addressed below. COMCO has defined four stages in the "Commercialization Investment" of Dr. Mills's new hydrogen energy source (Attachment A). Kline-Anderson has been asked to provide a "reality check" or a "sanity check" on the Phase I development program, and "red line" the schedule that comprises the first of the four stages (Attachment B). The descriptions of the Test Cells 1, 2 and 3 which were initially given to me were outdated, and needed additional work and recasting. Clarification of what these milestones are was necessarily an integral part of my task. The resultant redefinition of these milestones was finalized by Jim Kendall and is included as Attachment C.

As part of a Due Diligence process that has a bearing on funding levels and timing (staged funding). We (Kline-Anderson) take a conservative view of the technical aspects of this project. I have based my report strictly on my fact finding trip with Jim Kendall to HydroCatalysis Power Corporation (HPC) and the NovaTech labs, and the written information provided to me. In this role, I have been mindful that considerable investment funds are contemplated, and the planning that describes how these funds will be utilized is key to ensuring that resources will be used effectively and efficiently and towards the absolute success of COMCO. We have deemed it wise to err towards the conservative, allowing Technology Insights and PacifiCorp to make up their own minds about how much optimism to inject. Where I did not see a clear process underway, I have pointed that out so that Technology Insights, who has access to many more documents relevant to this technology, and who have months of study behind them about this technology, can incorporate my comments into the total picture.

Most importantly, the alterations in the revised schedule result in a planning document that represents the most likely outcome of the work to date at any given time in the progress of the work. Milestones have been revised to be natural breakpoints in the progress of work, so that now slips or advances in the work schedule may be easily accommodated. This schedule will continue to serve as a working document for tracking results of the investment, and can form the basis for allocation and reallocation of resources along the way. The intention is to provide COMCO management with additional information and working tools to ensure the overall success of this venture.

2. Review Background Material (Subtask 1)

A list of the documents I received and reviewed is in Attachment D.

My study was a technical evaluation of the process to commercialize this invention only, and I have not done a technical review of Dr. Mills's Hydrino Theory, or of the experiments that lead to the design of the vapor-phase reactor. For the purpose of this study, I have assumed that excess heat is evolved by these energy cells, that this result has been verified by independent laboratories, and that the phenomena is explained by Dr. Mills's Hydrino Theory. I reviewed all items in Attachment D only, thus, I have not reviewed the data or experimental methods from this previous work, which goes back several years. Neither have I attempted a review of Dr. Mills's Theory. Therefore I am not opining on the experimental history, or the theory in this report.

However, I saw nothing during my fact-finding trip that contradicted the assertions and representations made by HPC about any of their work, or about Dr. Mills's theory.

3. Visit to NovaTech and HPC Facilities to review the current status of activities relevant to the integrated schedule for development of a functional prototype unit. (Subtask 2)

As explained to me in my visits to HPC and NovaTech, by their personnel, and in conversations with Jim Kendall of Technology Insights, the HPC/NovaTech current plan as outlined is the following (points A through D):

(A) The most long-lived excess heat cell experiments were completed at Thermacore. Multiple experiments at Thermacore demonstrated excess power, but the work was abandoned because the results did not provide a basis for a commercial application.

The electrolytic cells were rejected as a design basis for a commercial unit due to the limitations in power density that they could achieve. In seeking economically viable power densities, the concept of the hydrino transition reaction was re-examined and a new energy cell design was invented from first principles. HPC asserts that the transition reaction can occur in the gas phase, as well as in aqueous solutions. If this assertion is proven true, this enables a new generation of hydrino energy cells to be built that take advantage of traditional chemical process ideas; such as continuous feed of reactants, high operating temperature, and continuous operation.

(B) It is the transition to this new type of cell that is the focus of Test Cell 1 work that is in progress at HPC and NovaTech. The objective of this Task is to demonstrate a cell that will operate repeatedly and controllably. The operating parameters have been defined as:

Operating Parameters
• Catalyst vapor pressure (catalyst concentration)   • Choice of catalyst   • Choice of hydrogen dissociation surface: filament or foam   • Molecular hydrogen gas pressure   • Atomic hydrogen gas pressure   • Filament operating temperature (current supplied to the filament)   • Cell hydrogen flow rate
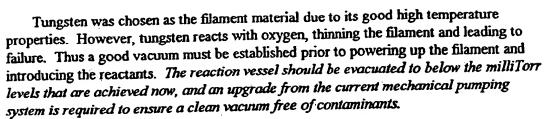
Optimal operating parameters are expected to be 2 Torr of potassium, 200 milliTorr of molecular hydrogen, and as high a filament temperature as possible to atomize as much hydrogen as possible. (1 atmosphere of pressure = 760 Torr). This information was based on the results of the quartz cell, and calculations by Dr. Mills.

(C) The design goals are listed in Attachment C. Most importantly, catalyst vapor pressure can be varied by controlling the temperature to the potassium iodide oven with an external heater. Previous designs have used heat from the filament to vaporize the potassium. The addition of this degree of freedom will permit the best operating vapor pressure for potassium to be documented. Secondly, hydrogen can be flowed through the cell continually, the first step in going towards a continuously working cell.

(D) Fabrication of a test bed, which I recommend be expanded to a conventional Test Fixture is underway at NovaTech. A Test Fixture will allow experimentation with different operating scenarios, by serving as a standard testing device for different designs of the energy cell. (See Section 4).

HPC Site Visit:

The current activity centers around a dramatic change in energy cell design. In changing design from the aqueous cells to vapor phase cells, the problem of getting atomic hydrogen and catalyst ions in the gas phase had to be solved. Bill Good, HPC's research director, has stated that potassium and rubidium both are active catalysts for the transition reaction process. Further he states that alkali halogens are the best chemical forms to utilize and that several salts were tested, and iodides were determined to be the best choice. According to Mr. Good, an operating temperature of greater than 730 C to keep the ions from condensing out on the walls of the vessel is required. He also presented the following information:

Initial testing was done with a quartz tube reaction vessel. Data from this tube indicate that optimal operating conditions will be 2 Torr of potassium ions, 200 milliTorr of molecular hydrogen with a filament temperature (reaction surface temperature) as high as possible (limit on the tungsten is 2000 C).

Tungsten was chosen as the filament material due to its good high temperature properties. However, tungsten reacts with oxygen, thinning the filament and leading to failure. Thus a good vacuum must be established prior to powering up the filament and introducing the reactants. *The reaction vessel should be evacuated to below the milliTorr levels that are achieved now, and an upgrade from the current mechanical pumping system is required to ensure a clean vacuum free of contaminants.*

Evolved heat is measured by differential calorimetry. HPC and NovaTech have invented a new high temperature calorimeter for this purpose. It is constructed from firebrick, and the energy evolved is measured as a changing heat gradient between two points located radially outward from the energy cell's center. As excess heat is evolved from the energy cell, the rise in temperature differential between the two points is measured. No experimental runs were attempted with any cells until calibration curves for the new calorimeter were stable and reproducible. It is critical to be meticulously careful with these calibrations, since the observable of excess heat will be the chief experimental result that will guide the optimization of these energy cells. *Meticulous thermal isolation and calorimetry that is above question is key to this process. It is the single most important issue for the overall success of the development plan.*

Recommendations:

Because the energy cell is not totally enclosed in the firebrick, but the ends of the cell protrude from it, there are two heat paths out of the cylindrical energy cell: Radially out through the firebrick, and axially out the ends of the cell. Since conduction and convection dominate over radiation for heat transfer mechanisms, it is reasonable to assume that the proportion of heat that flows via each path remains constant throughout any heat generating operation of the cell. If this proportionality does stay constant, then the measurement of excess heat recorded by the thermocouples located radially out from the center of the cell will indicate data accurately. This assumption may or may not hold up with the addition of the tungsten foam as well as it holds up for a simple tungsten filament. Final resolution of this issue will require construction of a "test bed calorimeter" that completely encloses and isolates the apparatus, like the conventional bomb calorimeter.

This test-bed standard calorimeter should be specified with multiple thermocouples, ten or twelve, that are monitored and recorded by a data acquisition system. Design and construction of this device will require additional materials and instrumentation beyond what is presently in place at HPC. This could be incorporated as part of the Test Fixture. *Because the thermal measurements are key to this project, the firebrick calorimeter must be fully characterized and calibrated to a standard calorimeter if possible.* If a commercial calorimeter cannot be brought in for standardization against a well known instrument, an acknowledged calorimetry expert can be brought in to independently study and confirm that the calorimeter is fully functioning appropriately. This expert can certify that the calorimeter is functioning properly, and that it is the best way to handle this high temperature situation.

An inherent limitation of this energy cell is the temperature limit of the stainless steel vacuum vessel. The vapor pressure of KI at 710 C is 1 Torr. To achieve 2 Torr, the temperature must be raised to 730 C. For the grade of stainless steel used, a temperature limit of 760 C has been specified, but Matt Ales at NovaTech is willing to push the limit up to 800 C. *Certainly commercial energy cell units will require an advanced materials solution, and the test cell development program must reflect this.*

Two test cells are slated for operation by HPC (TC1B and TC1C) to improve the understanding of the process by variation of key operational parameters. I have listed these parameters in the box above. *To map the multiple parameter-space of the performance of this energy cell, each parameter must be varied independently and systematically.* This data guides test cell design and will form the basis for understanding the dynamic characteristics of the prototype energy cell, and indicate requirements for process control instrumentation.

In addition to an upgrade of the vacuum system and test-bed calorimeter, additional testing equipment is required. A high quality stable power supply for the filament, additional thermocouples, and a hydrogen flow meter to measure molecular hydrogen delivered to the reaction vessel is a minimum equipment list for this task. At least two professionals full time should be devoted to this effort. A data acquisition system to monitor and record pressures, temperatures, current to the filament, and current to the potassium heater must be incorporated with these testing cells. This is an important step in the development and understanding of this technology and constitutes a conventional lab Test Fixture.

NovaTech Site Visit

The NovaTech team present included Richard (Hawk) Rochow, Matt Ales, and Lewis Walton. They have expanded their space to house this experiment. In our discussion with NovaTech a quartz energy cell encased in fire brick was described. This work was internally funded by NovaTech and designed to be a "quick and dirty" attempt at independent verification of the evolution of excess heat. It was a static system, capable of no gas recharge. Catalysts used were potassium nitrite and potassium iodide, with heat to the catalyst from the filament only: no independent control. Zirconia and alumina were used as insulators in this cell, with a marginal vacuum system. The calorimeter, which was originally constructed of calcium silicate (failure mode: warping), was replaced with the firebrick insulation that forms the basis for the current calorimeter. Here the simple firebrick delta-T method for measuring heat flow was developed. Results indicated 3% excess heat was evolved, with an estimated 2% uncertainty in the measurement.

In designing Test Cell 1, they described numerous significant design changes that were made based on their experience with the quartz cell. The quartz tube was replaced with a stainless steel vessel with an external catalyst reservoir. Internal aluminum oxide insulation was added to protect the stainless steel wall from thermal damage. A tungsten foam core for dissociation of hydrogen was installed to maximize tungsten surface area. Expected maximum centerline operating temperature is 1500 K, with an absolute

maximum at 1800 K, where the alumina will start dissociation. A flowing hydrogen gas system was installed.

Experimentation up to Oct. 16th had not resulted in a statistically significant observation of excess heat. NovaTech proposed several reasons for the failure of the cell to evolve heat. Among them are the following:

- Control of the catalyst location and partial pressure was not sufficient to deliver catalyst to the reaction volume at appropriate concentrations, and at the right moment in the experimental "run" of the cell.
- Large time constant of the calorimeter may be obscuring results.
- Failure of tungsten filament at high temperature and flow conditions.
- Possible contamination of the tungsten foam rendering it inactive for hydrogen dissociation.
- Contamination due to inadequate vacuum.
- Persistent contamination due to alumina insulators.

Recommendations:

To address these issues, they plan to run at higher centerline temperature to achieve greater dissociation of hydrogen gas to atomic hydrogen. They may run with the filament and without the foam. A turbomolecular vacuum pump has been acquired by NovaTech to be fitted to the energy cell. This addition will solve the problems of impurities to a large degree by improving the ultimate vacuum the system can reach, but cannot totally ameliorate the oxygen and water contamination that is the product of the slow outgassing of the thick, hot, alumina insulators. *This is seriously problematic and progress will be faster once the alumina is eliminated.*

A lengthy discussion of the alumina insulation highlighted the fact that it is a source of oxygen and water in vacuo, and due to the size of the insulators, will take a long, *long* time to bake out completely. These insulators will also retard heat flow to the surface of the cell for heat transfer in a heat exchanger. Several other choices for insulation were discussed and molybdenum foil emerged as the early favorite, due to its relatively cheap cost (compared to other advanced materials). *I recommend that this change be effected immediately, in the multi-layer geometry that NovaTech suggested. It will give their cell a higher temperature capability immediately, and speed progress.*

4. **Provide comments and recommendations regarding resource requirements for planned tasks leading to the fabrication and initial operation of a functional prototype unit. (Subtask 3)**

Test Cell 1

Performance milestone goals require demonstration of excess power over the noise level of the calorimeter (estimated at 2% in the delta T measurement by NovaTech), repeatably and sustained over hours.

Test Cell 1 is currently being modified at NovaTech. Several important issues have been identified that need work-arounds. The most fundamental is the vacuum quality.

While "perfect" mechanical pumps can achieve an ultimate vacuum of 40 milliTorr, this is usually right after a rebuild or general overhaul has been finished, and most pumps only get to 80 or 100 milliTorr, as both NovaTech and HPC have experienced. NovaTech has tried to stretch the quality of the vacuum they get by using the conventional fix: cyclic pumpouts and flushes with an inert gas. This is sound lab practice, and might be good enough if it weren't for the alumina insulators, which present a lengthy outgassing problem due to their thickness. Even after a reasonable "bake-out" period, oxygen and water due to the alumina may persist. *The NovaTech solution, to go to greater pumping capacity is a right choice. If they continue to flush with an inert gas, they might try dry nitrogen instead of helium, because it is cheaper.*

Thermal isolation of the energy cell and the firebrick calorimeter has been discussed above. I recommend that the firebrick calorimeter be redesigned for complete encasement of the energy cell, and calibrated to a known standard. This will be involved, but will pay off with increased accuracy in measurements. *The time constant of the calorimeter (response time) must also be clearly demonstrated, so we will know if results are being obscured.* NovaTech is already considering this problem by comparing the centerline temperature excursions to the delta-T measurement. The uncertainty in the delta-T measurement must clearly be established at 2%. This can be accommodated within the Test Fixture.

A significant materials problem has become evident in the operation of this test cell: The entire reaction vessel must be kept above the condensation temperature of potassium iodide (melting point 682 C). The operating temperature selected to achieve the desired vapor pressure of potassium ions in the cell is 710 to 730 C. Inorganic salts are not known for their reflux tendency back into a furnace, and it is unlikely that a substantial liquid phase of KI is resident in the cell. If the potassium ions or KI molecules were condensing out on any surface below 682 C no positive results in excess heat will be observed due to the absence of the reactant. Further, the potassium must be a lone ion to participate in the hydrino transition reaction. The clear indication is that the entire reaction vessel must be operated at temperatures of at least 730 C, and probably higher. In a commercial energy cell, higher operating temperatures (at the surface of the cell) are desirable, as this gives the cell superior heat transfer efficiency, *so solving this problem sooner rather than later is wise.*

The alumina insulators can probably be run at the desired temperature - however, due to their mass and geometry, it will lengthen the time for the cell to achieve thermal equilibrium at the operating temperature. Further, the problem of oxygen and water contamination from the alumina remains. Direct lab experience in scaleup operations requiring alumina material as pass through insulators or internal static separation units, underscores the need for lengthy bakeouts. The porosity of this material allows outside atmosphere to permeate it each time the vacuum is vented. *In this case the problem is critical enough that we recommend replacing it as soon as possible to ensure accurate results in testing.*

The proposed solution from NovaTech is to fashion a multiple foil insulator to protect the stainless steel walls from excess heat. This is a good solution for Test Cell 1 and should be implemented now. Not only is the thermal problem solved, but the contamination problem is eliminated, and the design for the cell is simplified. In the commercial cell, the vacuum wall itself must be fabricated from an advanced material. *It is prudent to begin testing and evaluation of materials now, as heat shields, in preparation for selecting the final reactor vessel material. This is a serious problem and will take some time to address fully.* It comprises a significant modification to the cell, therefore after its implementation the cell must be recalibrated with control runs. NovaTech estimated the cost for molybdenum foil to effect this change at about $15,000 for one cell. This may be underestimated, and this will be a one-time purchase, but if this solves the problem a much larger purchase of it will be needed.

Test Cell 1	Objective: To achieve a design of a cell that will operate repeatedly and controllably, and use as a basis to formulate a strategy for subsequent cell development
Design Goals:	**Status:**
Independently control catalyst vapor partial pressure (utilize an externally heated reservoir, no high temperature seals).	An external heater has been fitted to the catalyst reservoir, converting it into an oven.
Utilize a flowing hydrogen cell (prevent "fuel" starvation).	Hydrogen flows in to the reactor through the catalyst furnace.
Overcome the thermal limitations of previous vessels & insulation (keep stainless steel vessel sufficiently cool, but keep stainless steel vessel hot enough so potassium iodide catalyst precipitation is reduced).	Undergoing redesign and modification now, see above. Ultimately will require fabrication from advanced refractory materials.
Design and fabricate a relatively inexpensive test bed (allow for high surface area tungsten foams or powders, allow for various catalysts, investigate other materials, investigate different operating scenarios (T, P, flow, etc.)).	The initial model is in place at NovaTech, but requires a higher quality vacuum system and instrumentation linked to a data acquisition system to record results of different operating scenarios. See "Fabrication and Operation of Test Fixture" below.

To operate at these elevated temperatures all viton seals must be replaced with metal seals. This will require machining new flanges, and may require machining a new stainless steel reactor tube.

The best control protocol must be agreed upon and used consistently. A non-dissociating heat source should be considered for control runs of the calorimeter.

After the above modifications are completed and the energy cell is operating, it is reasonable to presume that one or more iterations of design and modification will be required. This will slip the schedule for Test Cell one considerably.

Other technical additions that NovaTech proposed and I also recommend are the following:

- Data acquisition system: to track thermocouples, gas flow, and current supplied to filament.
- Improved catalyst pressure control
- Attempt to eliminate catalyst losses to cool spots.
- Delta-T thermocouples at faster responding locations (and more than two)
- Greater range in power supply/controllable constant power source.

I estimate minimum personnel requirements for the NovaTech team at 4 people full time. This is significantly higher than their current level of effort.

Fabrication and Operation of the Test Fixture, TC1A and TC1B:

The concept of the Test Bed is important and should be expanded to be a conventional Test Fixture. The last design goal for the Test Cell 1 is to fabricate a test fixture to investigate operating scenarios (parameters). Instrumentation needed for optimization of the process will include the following: A constant power - power supply, additional pressure gauges, pumping system upgrade to improve the vacuum (impacts impurity level in the cell), and metering to monitor hydrogen gas flow into the cell. Acquisition of a residual gas analyzer to determine content of the reaction cell should be seriously considered.

This test fixture, instead of being an operating model, serves as a standard testing device for different designs of the prototype energy cell. It will support the development of auxiliary control systems to service the steady state and dynamic requirements of the energy cell (Test Cell 2 performance goals).

It will generate comparable test data all the way along the program, for each change in the energy cell. An automatic data acquisition system run by a dedicated computer is integral to this fixture. It measures all important operating parameters, including amount of reactants delivered over time to the cell, pressures, heat signatures from thermocouples from digital meters, etc. This is all saved to disc for every test run. A graphic paper printout of the data portrays different variables over time. This record-keeping provides a record that documents progress and shows whether milestones are being achieved. It

records a complete data set for analysis and troubleshooting of problems. This test fixture is common lab practice and requires standard instruments.

It is unwise and ill-advised to use a test cell that is incrementally modified and integrated into its own data gathering system for this purpose because any problem that may have occurred that was overlooked can skew results. A test fixture is a work station that, for example, has a multi-lead cable that is plugged into the energy cell under test. It is advisable that the firebrick calorimeter be a permanent part of the test fixture itself. The test fixture houses the metering devices and data acquisition system.

The redesign of TC1A and TC1B as independent test fixtures, with calorimeters that are calibrated to a standard, creates a data acquisition system that records all experimental events, and the results are kept in lab notebooks. This is useful for a number of reasons, among them financial and experimental, and for demonstration purposes. For demonstration to third parties, who will eventually want to see this data (OEM's), it provides a standard lab unit where all cells have been evaluated with results that are easily compared to each other. *This issue takes on even more significance since Test Cell 1 hasn't produced a positive result yet, in terms of excess heat.* As soon as the cells start generating excess heat, baselines for operations and outcomes will be automatically recorded in the test fixture, facilitating the optimization, and design/modification cycle.

This level of documentation - at each step - increases the overall probability of success of the Phase I program, and lays a foundation for interaction later with OEMs. A person with extensive laboratory experimental experience (advanced degree), and extensive management experience should be put in place to provide strong leadership to the design and testing teams. This leader will keep teams on task, and get them the materials/resources they need for quick work-arounds in between milestone reviews with management.

Conclusions:

The level of professionalism and care displayed by the NovaTech personnel is high and consistent. They appear organized, thorough, thoughtful and prepared to go forward. They have made a business based on prototyping hardware for space applications, which makes them experienced not only in hardware design and methods development, but in working with extreme operating conditions. In the case of space systems, hardware must withstand extremes of temperatures and pressure along with the possibility of frequent thermal cycles. This group is very well-qualified to lead the Test Cell development team and engineer these cells for scientific accuracy as well as functional reliability with a continual awareness of the requirements of the eventual commercial unit. They are a key resource for this project, and the depth, scope and experience that they bring to their work substantially increases the likelihood of the absolute success of this entire Phase I development program.

Their team would be more effective if it were augmented in several ways. They need an expert calorimetrist available to them for quick consultation concerning the operation and calibration of the new firebrick calorimeter. This would be a senior, perhaps retired

person who would be available for occasional discussions. They also need available to them an advanced materials expert, who they have already identified. As the program proceeds, this person will become more and more central to the effort, and should be brought in as soon as possible. Other additions will probably become necessary as the project evolves, and NovaTech has indicated an awareness of this and is ready to recruit expertise as it is required. Their demonstrated ability to identify quickly and solve problems that emerge throughout the course of this project, and assign appropriate personnel to work tasks is critical. This team should head the design team meetings for further clarification of performance goals and design issues for work in progress. They are best qualified to lead the Phase I Test Cell effort.

Another recommended addition to personnel is a veteran government-trained configuration management person who would be utilized at 1/2 or 3/4 time to provide tight configuration and release control for procurement records, non-design drawings, and design drawings. Scientists and engineers typically rely on files for this activity, and do not record this information systematically or completely in their lab notebooks. Files can be lost, or accidentally destroyed.

Test Cell 2

The resource requirements for accomplishing the design and performance goals of Test Cell 2 present a slightly different kind of problem. As the basis for this task, there will already exist an energy cell that produces excess heat over hours of operation. Meeting the goal of 24 hours of continuous operation will require that the auxiliary process controllers be functional and can feed reactants to the energy reaction volume of the cell reliably and steadily. It remains to be discovered if the performance goal of 1 watt per cubic centimeter in the steady state is enough for self-sustaining operation.

At this stage, the power that is generated will now include the heat necessary to sustain the reaction. As a development device, there is no provision for extraction of useful energy; its entire energy production is going in to sustaining its operating temperature, or to ambient losses. The power generated will balance the heat loss to ambient in steady state operation. In later work, when the energy extraction/utilization device (such as an operating field system) is introduced, all the excess power won't be devoted to running the energy utilization device. Some power will be pulled back to sustain the transition reaction in the energy cell, and other energy will be put into electrical feedback for hydrolysis of water to generate hydrogen. In a commercial device, the system will be optimized for these factors. This fraction of energy used to sustain the cell and generate hydrogen may be interpreted as a fuel cost.

Personnel requirements may need to be adjusted for this task, based on the experienced gained in completing Test Cell 1, and this decision should be incorporated in the final Test Cell 1 design review.

Test Cell 3 and the Functional Prototype Energy Cell

Continually during these tasks the COMCO Commercialization Team must stay in contact with the Test Cell Design team concerning issues related to manufacturabilty: scaleup considerations/constraints and market information. During these stages, the Phase I development program must become increasingly interactive. Monthly design reviews are recommended to facilitate this process.

Also a continual dialogue between the engineers who are building the test cells and the COMCO person responsible for future interaction with OEMs must center around the expectations and requirements that must be met for a functional prototype energy cell. A first step in this direction is Jim Kendall's "Conceptual Characterization of HydroCatalysis Turbine Application Options" (Attachment E), and the detailed description of one of the ten options, "S-1 Radiant Recirculating Boiler" (Attachment F). Interaction and dialogue must be ongoing to ensure that the Phase I development work is focused on the requirements of the field prototype, and aligned with the constraints of the energy utilization device that it will be integrated into. *This dialogue must be continual, although it may require only a low level of effort to maintain. This should be part of the "initial product options" line 62.*

Already this activity has indicated that the commercial energy cell must be small to accommodate high power density on the inside and good heat transfer on the outside of the cell. Initial dimensional estimates are two to four cm in diameter and as long as possible (constrained by the kinetics of the transition reaction). The cells must operate at high temperatures (above 730 C), must maintain a vacuum inside, hold up to pressurized air or water outside (for some options), and have good heat conduction to the walls of the cell to facilitate its role in a heat exchanger. *This activity is already generating intellectual property for COMCO.* These integrated designs must be carefully documented and treated as sensitive trade secrets. Patentability of these designs for devices must be explored.

Feedback from this team must be factored into the Test Cell 2 and Test Cell 3 design objectives. *In particular the startup method for initiating the transition reaction in the test cells, once they are operating as part of a heat exchanger must be considered and planned for by Test Cell 3.* For example, initial heating of the energy cells might require that the pressure wall incorporate selective surface reflection capability. Other design requirements will develop in the course of this Phase I program. *Frequent interaction and discussion between the Test Cell Design teams and the commercialization team at COMCO will ensure that these issues are dealt with early on in the process and efficiently.*

At the Test Cell 3 / Functional Prototype Energy Cell demonstration stage, a cohesive life cycle operation paradigm needs to be outlined. The analysis can be concluded regarding what redesigns may be necessary to demonstrate number of cycles, number of closedowns and restarts will be necessary and expected. Early marketing studies would help identify these constraints such as how often an operator can afford to shutdown and restart the unit. This life cycle analysis is part of the continual comparison of design

specifications and customer needs that goes on for the entire Phase 1 effort as a background activity. The design after this one will generate a demonstrable shut-down and startup system for the energy cell, that occurs without human intervention. Also an estimate of how many cycles the unit will be required to execute, and its operating cost parameters can be determined towards the end of the Phase I planning period.

5. Provide comments regarding the viability of the projected schedule and recommendations for adjustments as appropriate. (Subtask 4)

COMCO has created an aggressive schedule, clearly so that commercialization can proceed as rapidly as possible. When it was determined that there was no cogent listing of performance goals for the test cells (milestone definition), I drafted a set that Jim Kendall and I worked on so they could be included in this report. As a result, the milestones were designed to be natural breaks in the course of work (slip/advance points). Kline-Anderson's independent calculation of the time required to reach each milestone matches up well with the original estimates in the COMCO schedule (Attachment B) after the Test Cell 1 milestone. We have recommended that personnel be augmented in several areas to meet the time goals. Once this performance milestone has been reached, the remainder of the schedule should be reviewed.

In Phase I development programs, such as this one, timeline milestones are often difficult to predict and to achieve owing to the uncertainties in the nature of development work. In this case, a radical design change to the energy cell has been adopted (aqueous phase to vapor phase). *Until Test Cell 1 operates successfully, no one can say how much the schedule may slip, because there isn't a test cell that works yet.* Given that the delivery date for the Test Cell 1 report is 12/3, the design team for this is in a very tough spot. This means the work must be completed by Thanksgiving. Even with augmenting the design team as discussed above, it would be reasonable to add 8 weeks to this task, to provide for procurement and implementation of the moly foil, calibration of the calorimeter, and enough process control ability to sustain the reaction for several hours. At least two more complete design/modification iterations are recommended. It could be approximately December 15 before NovaTech has a cell that they can begin to optimize for power density and duration of run time. During this period, they will have addressed several performance goals: 4, 5, 6 (see box). But will only be in a position to begin on 1, 2 and 3. Allowing an additional eight weeks for looking at 1, 2, and 3, puts the milestone for Test Cell 1 at Feb. 15. This is a best case scenario and assumes no new fundamental design problems emerge.

```
Performance Goals Test Cell 1

1. Show excess power operating over the noise level of the calorimeter (2% in the delta T
   measurement). Target excess power generation is 10%
2. Sustainable over hours (limit condensation/precipitation of catalyst and oxidation of tungsten
   filament)
3. Repeatable demonstration of excess power.
4. Controllable (controlled approach to excess power operating conditions and stable operation while
   generating target level of excess power)
5. Operating temperature 1000 to 1400 degrees C in the "hot zone" reaction volume as measured by
   the type C thermocouple.
6. Better understanding of cell insulation and refractory materials requirements.
```

This is all non-trivial laboratory work that has to be done when changing a basic apparatus, and even with augmenting the NovaTech staff, people who are accustomed to this sort of problem, it will take time. This is a significant schedule slip that is not avoidable.

Another likely place for a schedule slip to occur is if the redesign, management review and go-ahead takes more than the one day that is allocated for this task. To address this issue, and ensure that management is prepared, before the milestone date, for possible reallocation of resources, monthly design reviews are strongly recommended. These reviews should be on site, and conducted by COMCO's project manager and consultants that are selected for this purpose.

Because of the unavoidable uncertainty in the timeline for the milestones, it is important to create a concrete and clear understanding of the work in progress so that adjustments can be made prior to the milestone reviews. Monthly meetings are not too frequent at this stage. This uncertainty cannot be avoided, but its impact has been minimized by the formulation of specific design and performance goals for each step of the way, so that COMCO management can track work closely. This is a conventional way to handle the risk elements involved in Phase I development

As the degrees of risk are removed, it becomes more possible to make a concrete schedule that the COMCO team can stick to. But this actually is not realistic to expect before the first testing of the functional prototype unit itself. After that point, it is Kline-Anderson's experience that total schedule slippage approaches about 6% per year (this will be in Phase II).

6. Conclusions of a Technical Nature

For successful commercialization of this device, three goals must be met:

1. Increase in the power density that the cell will evolve: A reasonable goal for this is 100 to 150 kW/liter reaction volume. This is the comparable figure for boilers (reference Jim's report). It is estimated that a figure as low as 50 kW/liter will be economically viable

in a commercial unit. The economic viability cutoff power density depends on the features, benefits and costs of the final system.

2. *Controllability of the process:* An increased understanding of the interdependence of the operating parameters, their interdependence (degree of coupling), and instrumentation to control each must be put in place. This will result, ultimately in the basis for process control at the industrial (field test unit) level. Initially, this will be a simple on/off switch, or, ideally, a dial-type control that will vary the energy output of the cell.

3. *Prolonged operating duration at a self-sustaining power level:* The cells must continue to evolve energy after a starting procedure has been executed, and all energy input into the cell withdrawn.

The program is silent about several important concerns: Safety issues, such as storage and disposal of hydrogen gas have not been addressed. Possible rate limiting steps that may prevent the technology from being scaled to economic viability have not been questioned. For example, what chemical kinetics and process dynamics can be anticipated and provided for early in this program? Is the input current in a linear relationship with power evolved, and does that impact scaleup? Are there hidden dynamic characteristics of the process that will preclude scaleup? Does this reaction have a self-limiting aspect, and is there a competing quench reaction.

7. Off-Task Unsolicited Observations

Early marketing studies need to identify how many times in a week or month an operator can afford to restart his unit, and later cell designs must address this. This is the type of commercialization and scaleup issue that will come up more and more often throughout this work. Commercialization of this technology will be highly interactive owing to the nature of the process. Design reviews each month at all labs, are critical to this effort, and the report from the review should have the same intensity and focus that I have given one.

The unit first shown to outsiders, must operate without human intervention. It should be as easy to turn on as throwing one switch, and all safety gating should be in place. A self-sustaining run mode with appropriate shut off is required. To get the maximum financial return from a third party, this unit should not be shown to anyone before it is ready. COMCO cannot show a unit that doesn't work well and then claim to be able to fix it later.

I am concerned about the lack of formal peer review throughout the years Dr. Mills's theory has been published. There has been some peer review of an informal unpublished nature on Dr. Mills's theory. I am aware of Englemann's book review (noted in Technology Insights Technical Assessment). It is surprising that there is not one independently published paper that reports on the fundamental work in his theory, since it

was first published in 1989. It is provocative in its use of the Maxwell non-radiative boundary condition, and the use of the 3-dimensional Dirac delta function. For example, the interpretation of the Planck constant and the particle behavior of the electron is very interesting, and these ideas would seem to attract comment and dialogue from others. However, there seems to be a high threshold for serious consideration of the theory by the physics community. This may be due, in part, to the fact that the theory is contrary and revolutionary, and developed by an individual with unorthodox credentials.

COMCO is already generating intellectual property *now*.

In all aspects of the technology, but particularly in the scaleup into the commercialization of the technology, constant attention must be paid to intellectual property protection. This activity includes accurate documentation of trade secrets, filing of patents, international PCT filings, and all other aspects of intellectual property regime maintenance.
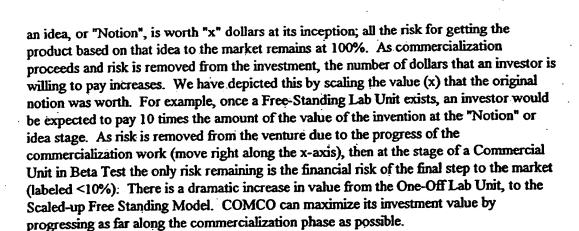
A COMCO Technical Advisory Board should be formed.

OEMs

An important part of the Phase I schedule involves discussions with OEMs. A focus of the Phase I work should be to prepare for these interactions from the beginning of the Test Cell work. We have expanded on the idea of a Test-Bed in the discussion of the Test Fixture above. The value of the Test Fixture, and the documentation that it creates about the energy generating process, is in these interactions with OEMs. *It is our opinion that work should continue in secret until an appropriate Demonstration Unit exists to show OEMs. This is not equivalent to Test Cell 2.*

The Demonstration Unit needs will be the first unit that anyone outside of COMCO, PacificCorp, HPC, or NovaTech is shown. This unit must operate without human intervention. It should be as easy to turn on as throwing a switch. All safety gating and release valves need to be in place, and it must start itself up independently, and convert itself over to the self-sustaining running mode automatically. This process should be evidenced to observers by easy to read meters. By throwing the "Off" switch, it must shut down in an appropriate and safe way. It is certainly acceptable to still have some engineering issues left, such as materials issues, and some scaleup. However, it is unwise to show a unit that doesn't work well (every time it is turned on), and add the assurance that it can be made reliable later.

Until this demonstration unit exists, we urge COMCO not to show intermediate results to anyone. Any disclosure of technology and progress contains risk for COMCO, and the potential benefit of the disclosure must be weighed against the risk. To get maximum return and involvement from an OEM, or other third party, an advanced level of development is advised. Our opinion of the "Conventional Wisdom" for return on investment during the commercialization stage is in the graph below. The amount an OEM will be willing to pay to get involved rises dramatically between a Sustainable Unit to a Stand Alone Functional Prototype. Return scales inversely with risk. On the graph

an idea, or "Notion", is worth "x" dollars at its inception; all the risk for getting the product based on that idea to the market remains at 100%. As commercialization proceeds and risk is removed from the investment, the number of dollars that an investor is willing to pay increases. We have depicted this by scaling the value (x) that the original notion was worth. For example, once a Free-Standing Lab Unit exists, an investor would be expected to pay 10 times the amount of the value of the invention at the "Notion" or idea stage. As risk is removed from the venture due to the progress of the commercialization work (move right along the x-axis), then at the stage of a Commercial Unit in Beta Test the only risk remaining is the financial risk of the final step to the market (labeled <10%). There is a dramatic increase in value from the One-Off Lab Unit, to the Scaled-up Free Standing Model. COMCO can maximize its investment value by progressing as far along the commercialization phase as possible.

Dr. Mills's desire to talk to OEMs too early is a risky approach and in fact goes against the conventional wisdom that you keep people away as long as you possibly can, and reduce the risks as far as you can, to realize the maximum financial return from your investment. If OEMs see a unit that is not working well, sustainably, consistently, or can't be turned on remotely with a safe shut-down, financial possibilities will be diminished.

COMCO Leadership

Finally, the role of strong leadership provided by COMCO cannot be overstated. The success of this Phase I effort depends on a high level of interactively, communication, and cooperation between PacifiCorp, COMCO, HPC and NovaTech. This can be achieved through regularly scheduled conference calls, e-mail, and monthly design review meetings at each site conducted by COMCO's project manager and select consultants selects. To perform on this aggressive schedule, no delays due to miscommunication can be permitted.

"Conventional Wisdom" Regarding Sales Price of An Opportunity (SP) to an OEM.

Sales Price Multiples (vertical axis): 30x, 25x, 20x, 15x, 10x, 5x, x

Amount of Risk Remaining in Development (right axis): <10%, 10-20%, 20-30%, 40-50%, 60-70%, 80-90%, 100%

Line labels: 30x, 20x, 10x, 5x

Horizontal axis categories:
- Notion
- One-off Lab Unit
- Free-Standing Lab Unit
- Replicable Manufac'bl Unit - Prototype Sized
- Scaled-up Model Free-Standing
- Fieldable Unit Fully Integrated
- Commercial Unit In beta test site

Attachment A

Commitment to Commercialization Investment
Phases I - IV.   (Technology Insights)

10.   Phase Structure/Commitment to Commercialization Investment

The following phases will overlap in time:

- Phase I - Functional Prototype (~2 years)

    Development and evolution of energy cells to address identified initial
    device application(s). Integration of hydrocatalysis energy cells with one
    or more energy utilization devices (e.g., gas turbine) for operation in a
    shop environment. Unit operation and modifications to identify and
    resolve resulting technical issues.

- Phase II - Commercial Prototype Engineering/Fabrication (~1-2 years)

    Design, supporting subcomponent testing (as necessary and practical),
    fabrication and factory acceptance testing of energy utilization devices for
    field operation in demonstration projects.

- Phase III - Demonstration/Commercial Unit Engineering (~1-2 years)

    Operation of prototypes, analysis of operating data, revisions to prototype
    design to establish final commercial design plus unit cost and reliability
    projections.
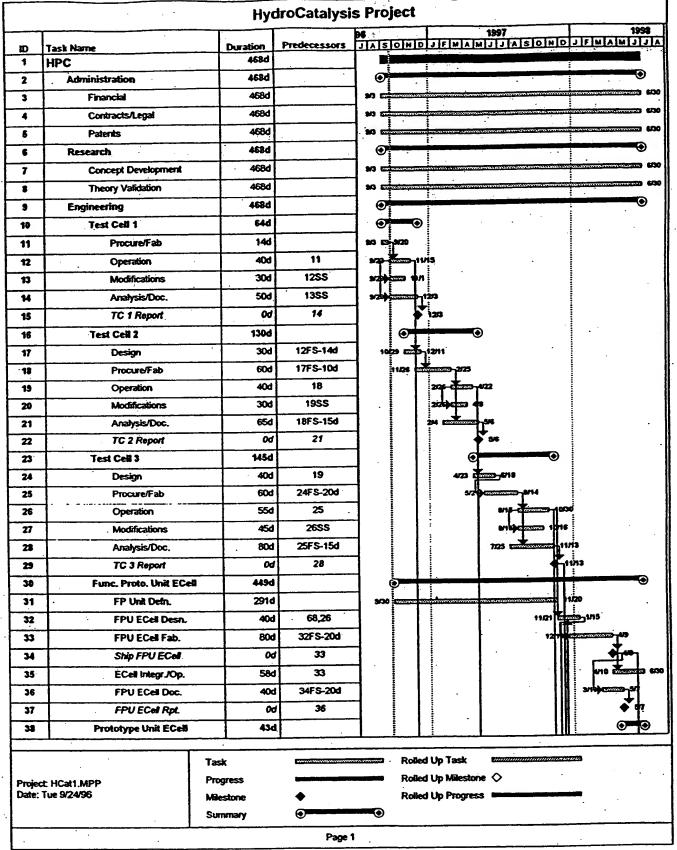
- Phase IV - Commercial Production Infrastructure (~1-2 years)
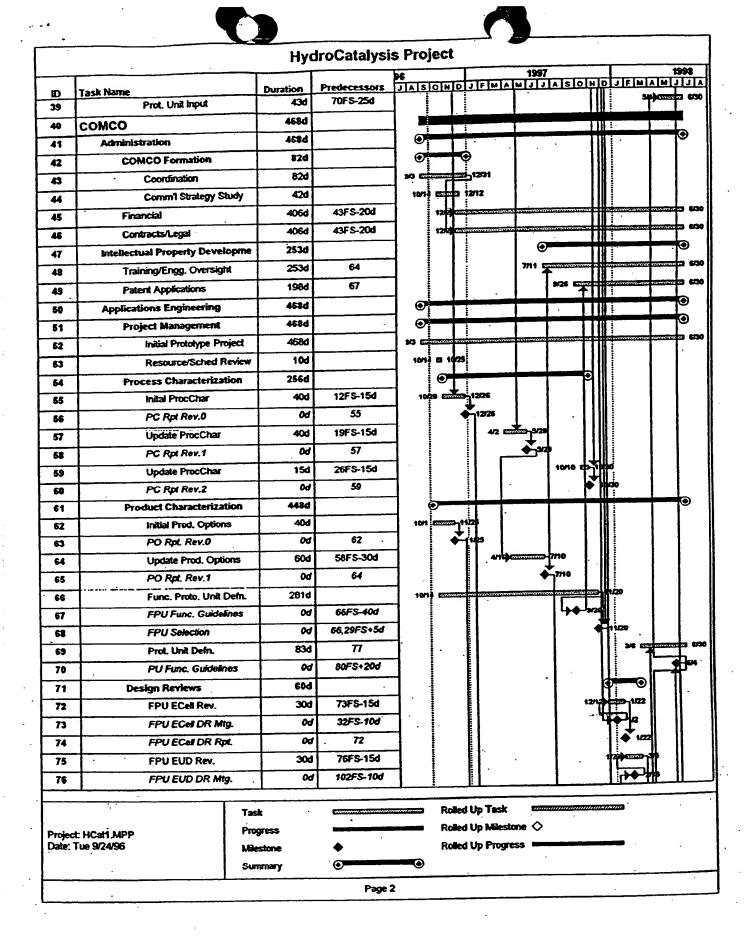
    Manufacturing engineering, retooling, quality assurance program, and
    production and factory acceptance testing of initial production units.

12

Attachment B
HydroCatalysis Project Phase I Schedule dated 9/24/96. (Technology Insights)

HydroCatalysis Project

ID	Task Name	Duration	Predecessors	96 / 1997 / 1998
1	HPC	468d		
2	Administration	468d		
3	Financial	468d		9/3 ... 6/30
4	Contracts/Legal	468d		9/3 ... 6/30
5	Patents	468d		9/3 ... 6/30
6	Research	468d		
7	Concept Development	468d		9/3 ... 6/30
8	Theory Validation	468d		9/3 ... 6/30
9	Engineering	468d		
10	Test Cell 1	64d		
11	Procure/Fab	14d		9/3 ... 9/20
12	Operation	40d	11	9/23 ... 11/15
13	Modifications	30d	12SS	9/23 ... 9/1
14	Analysis/Doc.	50d	13SS	9/23 ... 12/3
15	TC 1 Report	0d	14	12/3
16	Test Cell 2	130d		
17	Design	30d	12FS-14d	10/29 ... 12/11
18	Procure/Fab	60d	17FS-10d	11/26 ... 2/25
19	Operation	40d	18	2/26 ... 4/22
20	Modifications	30d	19SS	2/26 ... 4/8
21	Analysis/Doc.	65d	18FS-15d	2/4 ... 5/6
22	TC 2 Report	0d	21	5/6
23	Test Cell 3	145d		
24	Design	40d	19	4/23 ... 6/18
25	Procure/Fab	60d	24FS-20d	5/21 ... 8/14
26	Operation	55d	25	8/15 ... 10/30
27	Modifications	45d	26SS	8/15 ... 10/16
28	Analysis/Doc.	80d	25FS-15d	7/25 ... 11/13
29	TC 3 Report	0d	28	11/13
30	Func. Proto. Unit ECell	449d		
31	FP Unit Defn.	291d		9/30 ... 11/20
32	FPU ECell Desn.	40d	68,26	11/21 ... 1/15
33	FPU ECell Fab.	80d	32FS-20d	12/? ... 4/9
34	Ship FPU ECell	0d	33	4/9
35	ECell Integr./Op.	58d	33	4/10 ... 6/30
36	FPU ECell Doc.	40d	34FS-20d	3/10 ... 5/7
37	FPU ECell Rpt.	0d	36	5/7
38	Prototype Unit ECell	43d		

Task	▰▰▰▰▰	Rolled Up Task	▰▰▰▰▰
Progress	▬▬▬▬▬	Rolled Up Milestone	◇
Milestone	◆	Rolled Up Progress	▬▬▬▬
Summary	●▬▬▬●		

Project: HCat1.MPP
Date: Tue 9/24/96

Page 1

HydroCatalysis Project

ID	Task Name	Duration	Predecessors
39	Prot. Unit Input	43d	70FS-25d
40	**COMCO**	468d	
41	Administration	468d	
42	COMCO Formation	82d	
43	Coordination	82d	
44	Comm'l Strategy Study	42d	
45	Financial	406d	43FS-20d
46	Contracts/Legal	406d	43FS-20d
47	Intellectual Property Developme	253d	
48	Training/Engg. Oversight	253d	64
49	Patent Applications	198d	67
50	Applications Engineering	468d	
51	Project Management	468d	
52	Initial Prototype Project	468d	
53	Resource/Sched Review	10d	
54	Process Characterization	256d	
55	Initial ProcChar	40d	12FS-15d
56	PC Rpt Rev.0	0d	55
57	Update ProcChar	40d	19FS-15d
58	PC Rpt Rev.1	0d	57
59	Update ProcChar	15d	26FS-15d
60	PC Rpt Rev.2	0d	59
61	Product Characterization	448d	
62	Initial Prod. Options	40d	
63	PO Rpt. Rev.0	0d	62
64	Update Prod. Options	60d	58FS-30d
65	PO Rpt. Rev.1	0d	64
66	Func. Proto. Unit Defn.	281d	
67	FPU Func. Guidelines	0d	66FS-40d
68	FPU Selection	0d	66,29FS+5d
69	Prot. Unit Defn.	83d	77
70	PU Func. Guidelines	0d	80FS+20d
71	Design Reviews	60d	
72	FPU ECell Rev.	30d	73FS-15d
73	FPU ECell DR Mtg.	0d	32FS-10d
74	FPU ECell DR Rpt.	0d	72
75	FPU EUD Rev.	30d	76FS-15d
76	FPU EUD DR Mtg.	0d	102FS-10d

Task		Rolled Up Task	
Progress		Rolled Up Milestone	◇
Milestone	◆	Rolled Up Progress	
Summary			

Project: HCat1.MPP
Date: Tue 9/24/96

HydroCatalysis Project

ID	Task Name	Duration	Predecessors	96 / 1997 / 1998 (Gantt chart)
77	FPU EUD DR Rpt.	0d	75	
78	Readiness Reviews	30d		
79	FPU Opnl RR	30d	80FS-15d	
80	FPU ORR Mtg.	0d	109FS-10d	
81	FPU ORR Rpt.	0d	79	
82	New Concepts	158d		
83	Concept Development	158d	68	
84	Marketing	389d		
85	Vendor/OEM Interactions	383d		
86	Vendor/OEM Contacts	383d		
87	Select Lead V/OEM	0d	86SS+60d,65FS	
88	End User Interactions	384d		
89	Prospective Participants	384d		
90	Business Plans	361d		
91	Initial Bsns Plan	90d	56,63	
92	Bsns Plan Rev.0	0d	91	
93	Update Bsns Plan	60d	87	
94	Bsns Plan Rev.1	0d	93	
95	Update Bsns Plan	60d	102	
96	Bsns Plan Rev.2	0d	95	
97				
98	LEAD VENDOR/OEM	248d		
99	Engineering	248d		
100	Func. Proto. Unit	248d		
101	Func. Proto. Unit Input	90d	87	
102	FPU EUD Design	70d	68	
103	FPU Design Report	0d	102	
104	FPU Fab/Op Support	108d	103FS-20d	
105	Prototype Unit	43d		
106	Prot. Unit Input	43d	70FS-25d	
107	Manufacturing	108d		
108	Func. Proto. Unit	108d		
109	FPU Fab/Installation	80d	102FS-20d,34FF	
110	FPU Operating Manual	0d	109FS-10d	
111	FPU Operation	28d	109	

Legend:

Task	▭	Rolled Up Task	▭
Progress	▬▬	Rolled Up Milestone	◇
Milestone	◆	Rolled Up Progress	▬▬
Summary	◆▬▬◆		

Project: HCat1.MPP
Date: Tue 9/24/96

Page 3

9   Engineering
The task groups labeled Test Cell 1, 2 and 3 each represent a series of tests conducted with one or more devices of similar construction. The design tasks of the test cell series include design of auxiliary, control, and data gathering and analysis systems as needed to conduct the full scope of the test. The procurement/fabrication tasks include the assembly, calibration and initial shakedown operation of the equipment. The analysis/documentation tasks include initial definition and necessary adjustments of the test matrix, as well as data collection, integration, analysis and documentation in a test report.

10   Test Cell 1
A device whose design and fabrication is currently in progress at NovaTech under contract to HPC. Quartz tube in fire brick, designed to operate at 700 C,

16   Test Cell 2
A device currently envisioned to utilize a stainless steel outer container with internal ceramic insulation and designed to operate at 2000 C in the reaction zone.

23   Test Cell 3
A scaleup of the test cell 2 device designed for comparable operating temperature with a geometry evolving toward a heat exchanger configuration for the functional prototype unit energy cell.

30   Func. Proto. Unit ECell
The functional prototype unit includes an energy cell plus its auxiliaries and controls, in conjunction with an energy utilization device, as well as necessary instrumentation, data gathering and analysis equipment. The unit would be designed for operation in a controlled shop environment, with emphasis on understanding and resolving issues associated with the integration of an energy cell and energy utilization device over the range of expected operating conditions. Auxiliary and control systems for the energy cell would not necessarily be physically integrated with those of the energy utilization device.

54   Process Characterization
Interactions with HPC/NovaTech regarding cell design and operating experience to characterize the process as it relates to selection of an energy utilization device for initial development (e.g., temperature, pressure, power density, heat transfer and dynamic response characteristics).

61   Product Characterization
Integrating results from the process characterization and product options identification activities to develop functional guidelines for the initial unit, leading to selection of an initial unit concept for detailed design, fabrication and operation as a functional prototype. Subsequent integration of data from energy cell development and functional prototype experience to guide the development of a prototype unit.

82   New Concepts
Identification and development of new application concepts tailored to the characteristics of the HydroCatalysis process.

85   Vendor/OEM Interactions
Contacts with vendor/OEM organizations considered candidates for the lead vendor/OEM, leading to establishment of a contractual relationship to design, fabricate and operate the functional prototype unit.

88   End User Interactions
Support of PHI and/or HPC initiatives to involve additional end users (e.g., utilities, IPP companies) in COMCO, communications with COMCO owners, and coordination of the participation of representatives from COMCO owners in design reviews, operational readiness reviews, etc.

90   Business Plans
Development and documentation of long term plans and strategies for COMCO structure and operations.

100 Func. Proto. Unit
The functional prototype unit includes an energy cell plus its auxiliaries and controls, in conjunction with an energy utilization device, as well as necessary instrumentation, data gathering and analysis equipment. The unit would be designed for operation in a controlled shop environment, with emphasis on understanding and resolving issues associated with the integration of an energy cell and energy utilization device over the range of expected operating conditions. Auxiliary and control systems for the energy cell would not necessarily be physically integrated with those of the energy utilization device.

102 FPU EUD Design
EUD is energy utilization device (e.g., gas turbine, process heat supply), assumed to be a modification of an existing design to accommodate the HydroCatalysis energy cell.

105 Prototype Unit
The prototype unit would draw upon earlier experience to produce an integrated unit for field operation in one or more demonstration projects.

Attachment C

HydroCatalysis Project
Phase I - Functional Prototype
Energy Cell Development

The following material provides a definition of the design and performance objectives of an evolving series of HydroCatalysis energy cells leading to an energy cell unit to be integrated with an energy utilization device for the functional prototype unit. Titles refer to task summary entries in the HydroCatalysis project integrated schedule.

Engineering:

The task groups labeled Test Cell 1, 2 and 3 each represent a series of hardware and process design and engineering tests conducted with the vapor phase hydrino power cell (energy cell) that has been developed in collaboration at the HPC and NovaTech labs (note - current expectations are that NovaTech personnel performing the work will move within HPC or COMCO). The milestone reports for each test cell represent design evolution and engineering performance milestones in the evolution of this concept, not different concepts for the embodiment (physical implementation) of the hydrino power cell invention itself.

The design tasks of the test cell series include design of auxiliary, control, and data gathering and analysis systems as needed to conduct the full scope of the test. The procurement/fabrication tasks include the assembly, calibration and initial shakedown operation of the equipment. The analysis/documentation tasks include initial definition and necessary adjustments of the test matrix, as well as data collection, integration, analysis and documentation in a test report.

Test Cell 1

Objective: To achieve a design of a cell that will operate repeatedly and controllably, and use as a basis to formulate a strategy for subsequent cell development.

Design Goals:

- Independently control catalyst vapor partial pressure (utilize an externally heated reservoir, no high temperature seals)
- Utilize a flowing hydrogen cell (prevent "fuel" starvation)

- Overcome the thermal limitations of previous vessels & insulation (keep stainless steel vessel sufficiently cool, but keep stainless steel vessel hot enough so catalyst precipitation is reduced)
- Design and fabricate a relatively inexpensive test bed (allow for high surface area tungsten foams or powders, allow for various catalysts, investigate other materials, investigate different operating scenarios (T, P, flow, etc.))

Performance Goals:

- Show excess power operating over the noise level of the calorimeter (2% in the delta T measurement). Target excess power generation is 10%
- Sustainable over hours (limit condensation/precipitation of catalyst and oxidation of tungsten filament)
- Repeatable demonstration of excess power
- Controllable (controlled approach to excess power operating conditions and stable operation while generating target level of excess power)
- Operating temperature (other than the filament) 1000 to 1400 degrees C in the "hot zone" reaction volume as measured by the type C thermocouple
- Better understanding of cell insulation and refractory materials requirements

Optimal operating parameters expected to be: reaction zone partial pressures of 2 torr potassium iodode or 0.2 torr Rubidium iodide, 200 millitorr hydrogen, as high an operating temperature as possible, power density will be optimized by adjustment of partial pressures and temperatures within the limits of the device. Three Test Cell 1 devices have been fabricated: TC1A for operation by NovaTech directed toward the above objectives, TC1B and TC1C for operation by HPC to improve the understanding of the process by variation of key parameters. Test Cells TC1B and TC1C will have a partial Data Acquisition System.

Test Cell 2

Objective: Self-Sustained Operation (Long term (24 hour) operation without electrical input to the filament while maintaining reaction zone temperatures sufficient to support molecular hydrogen dissociation).

Design Goals:

- Higher temperature capability (eliminate oxide insulation through use of multi-layer insulation)

- Better vacuum system (reduce bake-out times required, improve quality of bake-out)
- Automated Data Acquisition System (DAS)
- Improved catalyst pressure control
- Attempt to eliminate catalyst "loss"
- Instrumentation for optimization of operating parameters (prep for scaleup)
- Delta-T thermocouples at faster responding locations
- Greater range in power supply/controllable constant power source
- Design and fabricate a relatively inexpensive test bed for operation at higher temperatures than Test Cell 1 (allow for high surface area tungsten foams or powders, allow for various catalysts, investigate other materials, investigate different operating scenarios (T, P, flow, etc.))

Performance Goals:

- Reliable and repeatable startup and operation in a self-sustained mode for periods in excess of 24 hours
- Quantitative understanding of power production as a function of key operating parameters
- Average power density in the reaction zone volume greater than 1 watt per cubic centimeter in steady state
- Reliable operation of supporting auxiliary systems
- Centerline temperature operation in the range 1300 - 2000 °°C

Test Cell 3:

Objective: An engineering redesign of the self-sustaining Test Cell 2 device, designed for comparable operating temperature with a geometry evolving toward a heat exchanger configuration for the functional prototype unit energy cell.

Design Goals

- Designed with advanced refractory materials, where required, from the outset
- Designed to eliminate net catalyst loss during normal operation, including slow reactions of catalyst with cell contents and vessel
- Provision for fabrication of multiple devices of varying length to investigate fuel and catalyst transport limits, with provision for axial data on performance for longer cells
- Provision for cell heat loss characteristics to support both initial heatup power requirements and heat transfer requirements of steady state operation beyond goal power densities
- Provision for parallel operation of two energy cell units serviced by a common power supply, hydrogen supply, catalyst supply and vacuum system

- The materials and design of this cell will provide the basis for study of commercial scaleup in terms of materials choice for function and price of the Functional Prototype Unit Energy Cell
- Analytical projection of sufficient operating lifetime for key materials
- Provision for removal of reaction products or foreign gases during long term operation

Performance Goals

- Reliable and repeatable startup and operation in a self-sustained mode
- Operation of an energy cell in a self-sustained mode for a period in excess of one week
- Average power density in the reaction zone volume greater than 10 watts per cubic centimeter in steady state
- Stable startup and operation of two or more energy cells supported by a common power supply, hydrogen supply, catalyst supply and vacuum system
- Quantitative data on the effect of energy cell length on performance
- Quantitative data supporting the key materials design lifetime analysis

Functional Prototype Unit Energy Cell

Objective: Parallel energy cells, as well as necessary instrumentation, data gathering and analysis equipment designed and fabricated for operation in conjunction with an energy utilization device. The resulting functional prototype unit (combination of hydrocatalysis energy cell unit and energy utilization device) will be designed for operation in a controlled shop environment, with emphasis on understanding and resolving issues associated with the integration of an energy cell and energy utilization device over the range of expected operating conditions. This program may be under the auspices and largely funded by an OEM.

Design Goals:

- An energy cell unit comprised of multiple energy cells operating in parallel and serviced by a common power supply, hydrogen supply, catalyst supply and vacuum system
- Provisions for automated startup and operation of the energy cell unit meeting the environmental and control requirements of the energy utilization device while operating in a controlled shop environment (Auxiliary and control systems for the energy cell would not necessarily be physically integrated with those of the energy utilization device)
- Energy cell unit capability (startup, dynamic response, power production, lifetime) as required to support the energy utilization device over a range of conditions covering the planned test matrix
- OEM input

4

Performance Goals:

- Reliable and repeatable startup and operation
- Power production consistent with the design operating range of the energy utilization device
- Stable operation and dynamic response characteristics consistent with the requirements of the energy utilization device
- Satisfactory operation over the conditions of the planned test matrix
- OEM input

5

Attachment D

List of Documents received by Kline-Anderson Inc. as background material from HPC and Technology Insights.

HPC:
Confidential Business Summary
Confidential Short Business Summary
"Fractional Quantum Energy Levels of Hydrogen" Fusion Technology, Nov. 1995.
Confidential Paper "Fractional Quantum Energy Levels of Hydrogen Representative Recent Results Prepared For Kline Anderson"
Book review by Dr. Reinhart Engelmann
Confidential Company Presentation
Confidential Protocols:
    Search For the Mills Hydrino: An Extreme UV Spectroscopy Proposal
    Measurement of Excess Heat From Hydrino Production
    Protocol For the Synthesis of Dihydrino Molecules
    Protocol For Heat Measurements With the High Temperature Vapor Phase Cell
    Protocol for Heat Measurements With the AtMar Glass Lamp
    Protocol for Calvet Measurements of the High Temperature Vapor Phase Cell
    Carbon XPS Protocol
    Gas Phase Hydrocatalysis: Proof of Principal Potassium Carbonate Coated Nickel
        Hydride Experiments
One Kilowatt Electric Prototype Proposal

Technology Insights:
HydroCatalysis Technical Assessment, August 30, 1996

"Conceptual characterization of HydroCatalysis Turbine Application Options"
(Technology Insights).

COMCO Technical Support Workscope

Conceptual Characterization of HydroCatalysis
Turbine Application Options

1.0 Objective

Identify steam and gas turbine options for power generation using the HydroCatalysis process and characterize each option in terms of conceptual configuration, environmental conditions imposed on a HydroCatalysis energy cell, existing experience and precedence, and system design and development issues. Select one or more preferred options for continued evolution in concert with the ongoing development of the energy cells.
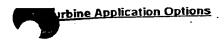
2.0 Background

The initial application of the HydroCatalysis process, to be developed jointly by COMCO and BlackLight Power, is anticipated to be for power generation utilizing either a steam or gas turbine. Since the fuel cost of the HydroCatalysis process is anticipated to be small, corresponding to the amortized capital and operation costs associated with production of hydrogen from water, achieving high efficiency is of lesser importance than for conventional power generation technologies. This will reduce the importance of efficiency in the optimization of the overall unit design primarily to its effect on capital cost. The options identified for further definition are intended to span the range of likely approaches for power generation, with expected significant variations in demands on the development of the HydroCatalysis energy cell, in design and development requirements for the power conversion equipment, and in projected commercial unit capital costs. The overall objective is to narrow the field of options being considered with the intent of arriving at one or more functional prototype units for near term development.

3.0 Options to be Addressed

The system configuration options listed below will be considered along with additional options which may be identified in the course of the work. Initial conceptual information is provided in an appendix to this document as a starting point for each configuration and to illustrate the approach to be taken and the information to be developed.

3.1 Steam Turbine

For the steam turbine options, the interface with the energy cell will be either directly or indirectly with a steam boiler. In light of the decreased importance of efficiency, lower pressure saturated or moderately superheated steam, similar to the

---

steam conditions in commercial water reactor power plants may be appropriate. The following steam turbine options, as defined in the appendix, will be considered.

S-1   Radiant Recirculating Boiler

S-2   Radiant Once-Through Boiler

S-3   Natural Convection Recirculating Boiler

S-4   Forced Convection Once-Through Boiler

S-5   Forced Convection Intermediate Loop Boiler

3.2 Gas Turbine

Gas turbine options will include open and closed cycles, with cycle efficiency to be addressed in a manner consistent with the approach for the steam cycles. The following gas turbine options, as defined in the appendix, will be considered.

G-1   Radiant Open Cycle

G-2   Forced Convection Open Cycle

G-3   Forced Convection Intermediate Loop Open Cycle

G-4   Radiant Closed Cycle

G-5   Forced Convection Closed Cycle

4.0 Scope of Activities

This effort will encompass the activities defined below.

4.1 Option Characterization

Using the material in the appendix as a starting point, characterize the options in sufficient detail to support the selection of one or more preferred options for further development as candidate(s) for a functional prototype. The following information will be developed for each option:

- **Concept Strengths** - Expand and quantify the list of positive attributes identified in the appendix

- **Design Issues** - Expand and quantify the list of design issues identified in the appendix

- **Energy Cell Environment** - Quantify the energy cell environmental parameters identified in the appendix (with additional parameters if appropriate)

- **Development Requirements** - Identify the scope of activities for development of the functional prototype and commercialization of the concept

- **Market Potential** - Identify the range of products (size range, applications) and estimate the unit costs for volume production

The degree of detail and level of confidence in the results will be consistent among the options addressed and sufficient to support a comparison for the purpose of narrowing the field of options under consideration. The results will be documented in a product options report in a format consistent with the information in the appendix, with additional considerations noted above included.

4.2 Preferred Option(s) Selection

Using the results developed by the work defined in the previous section, a meeting will be held to select the preferred option or options for further definition and iteration with energy cell development as a basis for the functional prototype unit.

4.3 Preferred Option(s) Development

Continue the design and characterization of the selected option(s) in support of the functional prototype unit development and COMCO commercialization plans.

Appendix - Turbine Application Options Conceptual Summary

Steam and gas turbine power conversion system options for the application of the HydroCatalysis process are defined in summary form on the following pages. This information is provided as a starting point for an effort to further develop and characterize the options, leading to the selection of one or more preferred concepts for further development. The options as defined here may be modified or more attractive options developed in the course of the work. The following options are identified:

S-1   Radiant Recirculating Boiler

S-2   Radiant Once-Through Boiler

S-3   Natural Convection Recirculating Boiler

S-4   Forced Convection Once-Through Boiler

S-5   Forced Convection Intermediate Loop Boiler

G-1   Radiant Open Cycle

G-2   Forced Convection Open Cycle

G-3   Forced Convection Intermediate Loop Open Cycle

G-4   Radiant Closed Cycle

G-5   Forced Convection Closed Cycle

The concept strengths and design issues are intended to address considerations external to the energy cells as well as demands placed on the design and operation of the energy cells. It is assumed that all of the options will be based on a self-sustaining energy cell design (i.e., no electric power input required in the power operation range). Based on current understanding of the HydroCatalysis process, this is further assumed to require the achievement of elevated temperature conditions (e.g., > 1500°C) in the reaction zone of the energy cell. Thus the need for high temperature materials and the resulting design issues for the energy cells is considered applicable for all of the options.

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Option S-1   Radiant Recirculating Boiler

Precedents

ABB/Combustion Engineering, Foster Wheeler oil, gas and coal fired steam boilers.

Summary Description

A bank of cylindrical HydroCatalysis energy cells is positioned adjacent to a bank of boiler tubes inside an insulated container with a reflective inner surface. A movable mirror lattice between the energy cells and boiler tubes is used to control heat transfer from the energy cells during startup and power operation. The boiler circuit is a natural convection recirculating loop with a steam drum containing steam separation equipment to meet the minimum inlet steam quality requirements of the turbine.

Concept Strengths

1. Low external pressure on energy cells

2. No flow induced structural loads on energy cells

3. Control of energy cell heat losses during startup

4. Boiler tube temperature relatively constant over the tube length and over the load range

Design Issues

1. Accommodation of thermal expansion

2. Energy cell temperature variation characteristics over the load range

3. Radiant panel heat flux - size requirements

Energy Cell Environment

1. Temperature distribution and operating range

2. Startup and control requirements

PHI CONFIDENTIAL *

Figure S-1 Radiant Recirculating Boiler

Steam Turbine-Generator

Generator

LP Turbine

IP Turbine

Cooling Tower

Circ Water Pump

Condenser/ Hotwell

Condensate Pump

Deaerator

Feedwater Pump

Steam Drum

Boiler Tube Panel

Mirror Lattice Panel

Energy Cell Panel

Mirror Surface Insulation

Mirror Panel Actuator

Hydrogen Manifold

Catalyst Manifold

Vacuum Manifold

Gas Cell Boiler

Technical Support Workscope

PHI CONFIDENTIAL *

Option S-2   Radiant Once-Through Boiler

Precedents

Babcock & Wilcox oil, gas and coal fired steam boilers.

Summary Description

A bank of cylindrical HydroCatalysis energy cells is positioned adjacent to a bank of boiler tubes inside an insulated container with a reflective inner surface. A movable mirror lattice between the energy cells and boiler tubes is used to control heat transfer from the energy cells during startup and power operation. The boiler circuit is a forced convection once-through system producing superheated steam.

Concept Strengths

1. Low external pressure on energy cells

2. No flow induced structural loads on energy cells
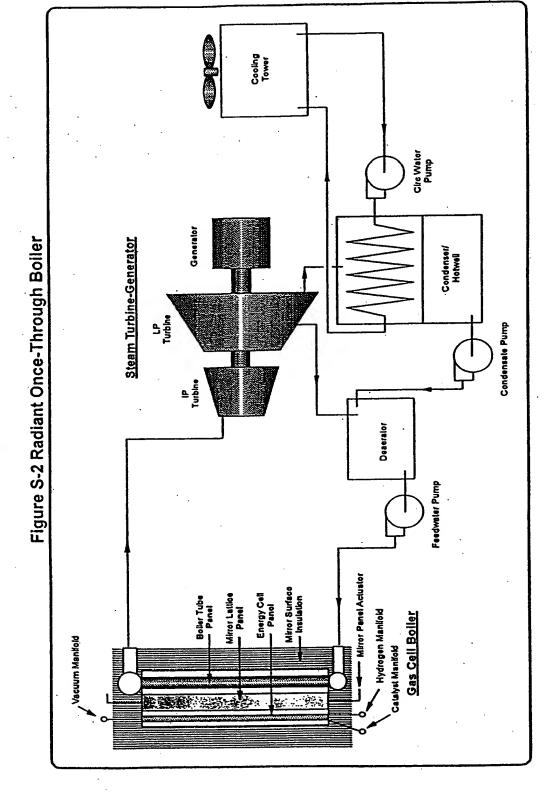
3. Control of energy cell heat losses during startup

Design Issues

1. Accommodation of thermal expansion

2. Energy cell temperature variation characteristics axially and over the load range

3. Radiant panel heat flux - size requirements

4. Boiler tube stability

5. Boiler startup and dynamic control requirements

Energy Cell Environment

1. Temperature distribution and operating range

2. Startup and control requirements

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Figure S-2 Radiant Once-Through Boiler

Steam Turbine-Generator

Gas Cell Boiler

Option S-3   Natural Convection Recirculating Boiler

Precedents

General Electric Boiling Water Reactors, U-tube steam generators for Westinghouse and ABB/Combustion Engineering Pressurized Water Reactors.

Summary Description

The energy cells are placed in tubes projecting into the boiler vessel in a bayonet configuration with external support grids. Recirculating water from the swirl vane separator and steam dryer mix with incoming feedwater, resulting in moderate subcooling at the bottom. The energy cell surface conditions are liquid convection in the bottom region, changing to nucleate boiling over the majority of the cell length.

Concept Strengths

1. High energy cell surface heat flux capability

2. Stable cell surface temperature and heat removal characteristics

3. Energy cell surface temperature relatively constant over the tube length and over the load range

Design Issues

1. Achieving self-sustaining energy cell temperature conditions during startup

2. Accommodation of energy cell internal thermal expansion

3. Single-ended access for hydrogen, catalyst and vacuum manifolds

Energy Cell Environment

1. External pressure range

2. Temperature distribution and operating range

3. Flowrates and flow induced loads

4. Startup and control requirements

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Figure 6-3   Natural Convection Recirculating Boiler

Steam Dryer
Swirl Vane Seperator
Pressure Vessel
Downcomer
Energy Cells
Tubesheet
Catalyst Manifold
Hydrogen Manifold
Vacuum Manifold

Gas Cell Boiler

Steam Turbine-Generator

Generator
LP Turbine
IP Turbine

Cooling Tower

Circ Water Pump

Condenser/ Hotwell

Condensate Pump

Deaerator

Feedwater Pump

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Option S-4   Forced Convection Once-Through Boiler

Precedents

Babcock & Wilcox steam generators for Pressurized Water Reactors.

Summary Description

The energy cells are placed in tubes projecting through the boiler vessel tubesheets with tube support grids on the shell side. Feedwater enters the bottom of the vessel on the shell side and exits as moderately superheated steam (sufficient to preclude moisture carryover from dynamic variations or non-uniform spatial effects. The energy cell surface conditions are single phase liquid convection in the bottom region, changing sequentially to nucleate boiling, film boiling and single phase vapor convection at the top.

Concept Strengths

1. Simplicity of boiler internals

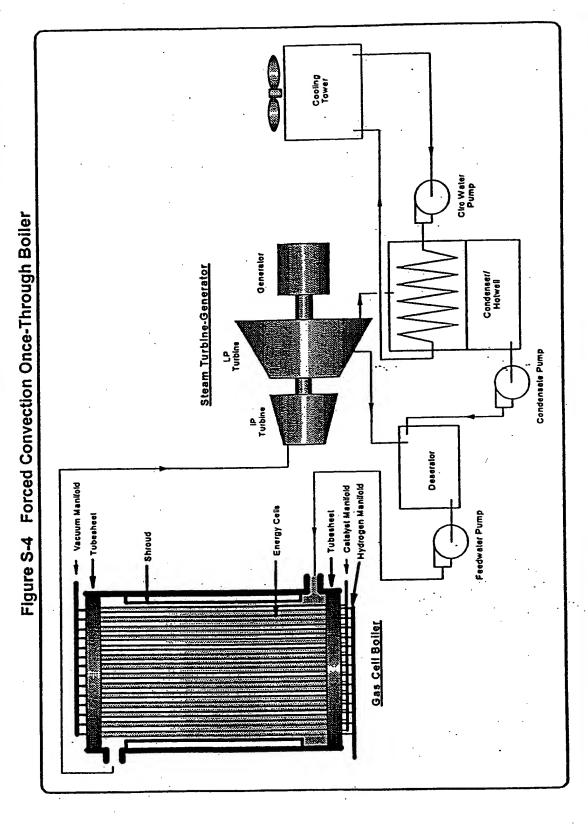2. High energy cell surface heat flux capability in the single phase liquid and nucleate boiling zones

Design Issues

1. Accommodation of thermal expansion in energy cells and between tube bundle and vessel (may require bellows or sliding seals)

2. Achieving self-sustaining energy cell temperature conditions during startup

2. Energy cell temperature response characteristics over the load range

3. Axial movement of heat transfer zones during load changes

Energy Cell Environment

1. External pressure range

2. Temperature distribution and operating range

3. Flowrates and flow induced loads

4. Startup and control requirements

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Figure S-4   Forced Convection Once-Through Boiler

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Option S-5   Forced Convection Intermediate Loop Boiler

Precedents

Helium cooled reactor (Peach Bottom, Fort St. Vrain, AVR), or carbon dioxide cooled reactor (Magnox, AGR) primary loop/steam generator.

Summary Description

HydroCatalysis energy cells are placed in tubes penetrating a heat exchanger vessel containing a pressurized gas (e.g., He, CO_2) heat transfer fluid. A gas circulator provides forced convection heat transfer on the shell sides of the heat exchanger and a steam generator. A helical coil once-through steam generator providing superheated steam is shown, but variations could include straight tube units as well as recirculating units providing saturated steam.

Concept Strengths

1. Independent control of energy cell environment (pressure, temperature, flow) over the startup and power operation range

2. Independent design of energy cell heat exchanger to accommodate power density and dynamic characteristics of the HydroCatalysis process

Design Issues

1. Development, capital and operating cost

2. Flow induced static and dynamic loads

3. Achieving self-sustaining energy cell temperature conditions during startup
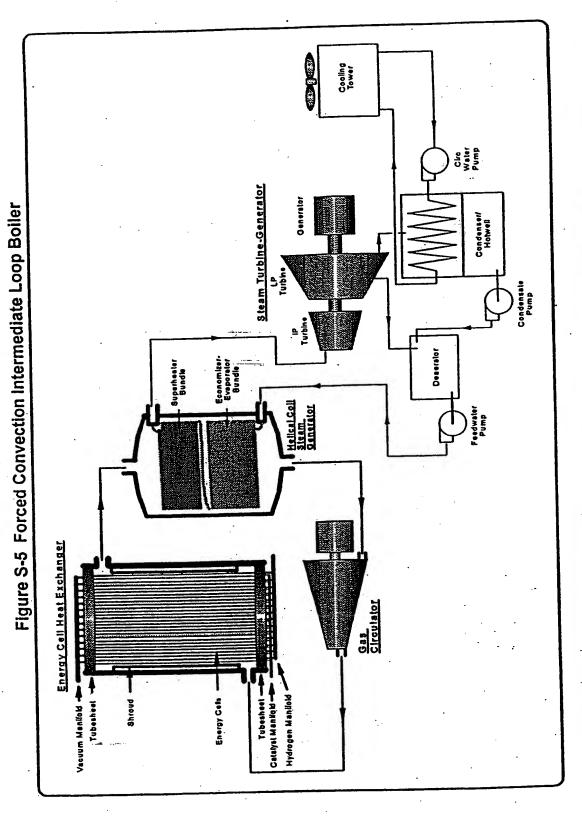
4. High temperature design of energy cell heat exchanger and steam generator vessel and internals, and accommodation of thermal expansion

Energy Cell Environment

1. External pressure range

2. Temperature distribution and operating range

3. Flowrates and flow induced loads

4. Startup and control requirements

Technical Support Workscope

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Figure S-5 Forced Convection Intermediate Loop Boiler

* PHI Confidential Information – Work Product for Hire Property of PHI

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Option G-1   Radiant Open Cycle

Precedents

To be identified.

Summary Description

A bank of cylindrical HydroCatalysis energy cells is positioned adjacent to a bank of heat exchanger tubes inside an insulated container with a reflective inner surface. A movable mirror lattice between the energy cells and heat exchanger tubes is used to control heat transfer from the energy cells during startup and power operation. The heat exchanger tubes contain pressurized air, with pressures determined by the characteristics of the gas turbine.

Concept Strengths
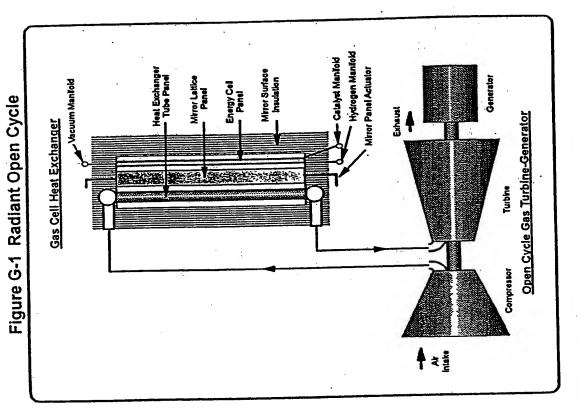
1. Low external pressure on energy cells

2. No flow induced structural loads on energy cells

3. Control of energy cell heat losses during startup

4. Simple flow circuit

Design Issues

1. Radiant energy cell panel and heat exchanger tube panel heat flux – size requirements

2. Axial variation in heat exchanger tube temperature/heat transfer from energy cells

3. Accommodation of thermal expansion

Energy Cell Environment

1. Temperature distribution and operating range

2. Startup and control requirements

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Figure G-1 Radiant Open Cycle

Gas Cell Heat Exchanger

- Vacuum Manifold
- Heat Exchanger Tube Panel
- Mirror Lattice Panel
- Energy Cell Panel
- Mirror Surface Insulation
- Catalyst Manifold
- Hydrogen Manifold
- Mirror Panel Actuator

Exhaust
Generator
Turbine
Compressor
Air Intake

Open Cycle Gas Turbine-Generator

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Option G-2   Forced Convection Open Cycle

Precedents

To be identified.

Summary Description

HydroCatalysis energy cells in tubes penetrate a heat exchanger pressure vessel, with pressurized air in crossflow over the tubes. Air from a gas turbine compressor flows to the vessel inlet, and heated air from the vessel outlet flows to the inlet of the power turbine, with pressures determined by the characteristics of the gas turbine. Self-sustaining energy cell temperature conditions are achieved during startup by combustion of hydrogen on the shell side of the heat exchanger, analogous to operation of conventional combustion turbines.
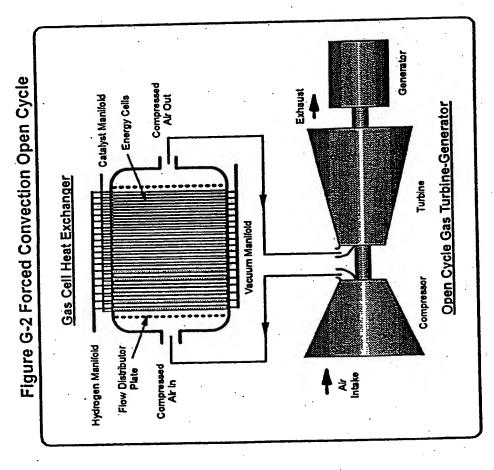
Concept Strengths

1. Potential for rapid startup using combustion bootstrap

2. Effective energy cell heat removal - relatively compact design

3. Simple flow circuit

Design Issues

1. Flow induced static and dynamic loads on energy cell tubes

2. Accommodation of thermal expansion and air temperature rise across heat exchanger

3. Energy cell dynamic response requirements

4. High temperature design of gas cell heat exchanger vessel and internals

Energy Cell Environment

1. External pressure range

2. Temperature distribution and operating range

3. Flowrates and flow induced loads

4. Startup and control requirements

Technical Support Workscope

Figure G-2 Forced Convection Open Cycle

Gas Cell Heat Exchanger

Hydrogen Manifold
Catalyst Manifold
Energy Cells
Compressed Air Out
Flow Distributor Plate
Compressed Air In
Vacuum Manifold

Exhaust
Generator
Turbine
Compressor
Air Intake

Open Cycle Gas Turbine-Generator

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Option G-3   Forced Convection Intermediate Loop Open Cycle

Precedents

Externally Fired Combined Cycle demonstration project at Pennsylvania Electric Company Warren Station, developed by Hague International in cooperation with Black & Veatch, Foster Wheeler, and Allison Engine Company.

Summary Description

HydroCatalysis energy cells are placed in tubes penetrating a heat exchanger vessel containing a pressurized gas (e.g., He, CO_2) heat transfer fluid. A gas circulator provides forced convection heat transfer on the shell side of the energy cell heat exchanger and the tube side of a gas/air heat exchanger. Pressurized air from a gas turbine compressor flows to the shell side of the gas/air heat exchanger and heated air returns to the inlet of the power turbine.
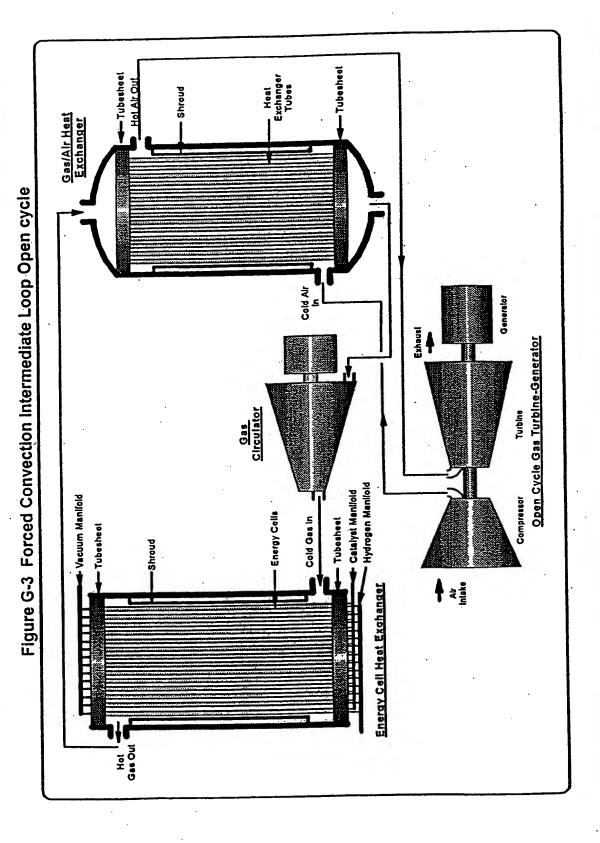
Concept Strengths

1. Independent control of energy cell environment (pressure, temperature, flow) over the startup and power operation range

2. Independent design of energy cell heat exchanger to accommodate power density and dynamic characteristics of the HydroCatalysis process

Design Issues

1. Capital and operating cost
2. Flow induced static and dynamic loads
3. Achieving self-sustaining energy cell temperature conditions during startup
4. High temperature design of energy cell heat exchanger and gas/air heat exchanger vessel and internals, and accommodation of thermal expansion

Energy Cell Environment

1. External pressure range
2. Temperature distribution and operating range
3. Flowrates and flow induced loads
4. Startup and control requirements

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Figure G-3 Forced Convection Intermediate Loop Open cycle

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Option G-4   Radiant Closed Cycle

Precedents

Oberhausen II helium turbine plant, HHV gas turbine test facility (Germany).

Summary Description

A bank of cylindrical HydroCatalysis energy cells is positioned adjacent to a bank of heat exchanger tubes inside an insulated container with a reflective inner surface. A movable mirror lattice between the energy cells and heat exchanger tubes is used to control heat transfer from the energy cells during startup and power operation. The heat exchanger tubes contain pressurized gas (e.g., helium), with pressures determined by the characteristics of the gas turbine cycle.

Concept Strengths

1. Low external pressure on energy cells

2. No flow induced structural loads on energy cells

3. Control of energy cell heat losses during startup

4. Controlled pressure, chemistry environment of turbine blades and heat exchanger tubes

Design Issues

1. Development, capital and operating costs

2. Radiant energy cell panel and heat exchanger tube panel heat flux - size requirements

3. Axial variation in heat exchanger tube temperature/heat transfer from energy cells

4. Accommodation of thermal expansion

Energy Cell Environment

1. Temperature distribution and operating range

2. Startup and control requirements

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Figure G-4 Radiant Closed Cycle

Gas Cell Heat Exchanger

Vacuum Manifold

Heat Exchanger Tube Panel
Mirror Lattice Panel
Energy Cell Panel
Mirror Surface Insulation

Catalyst Manifold
Hydrogen Manifold
Mirror Panel Actuator

Generator

Turbine

Closed Cycle Gas Turbine-Generator

Compressor

Recuperator

Precooler

Clto Water Pump

Cooling Tower

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Option G-5   Forced Convection Closed Cycle

Precedents

Oberhausen II helium turbine plant, HHV gas turbine test facility (Germany)..

Summary Description

HydroCatalysis energy cells in tubes penetrate a heat exchanger pressure vessel, with pressurized gas (e.g., helium) in crossflow over the tubes. Gas from a gas turbine compressor flows through a recuperator heat exchanger to the vessel inlet, and heated gas from the vessel outlet flows to the inlet of the power turbine. The gas pressure is determined by the characteristics of the gas turbine cycle.

Concept Strengths

1. Effective energy cell heat removal - relatively compact heat exchanger design

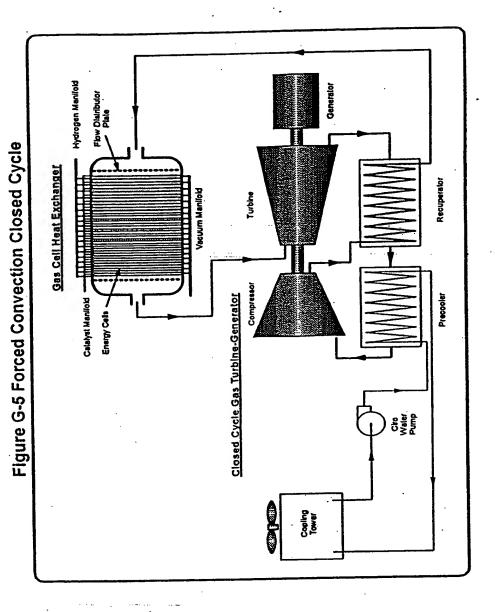2. Controlled pressure, chemistry environment of turbine blades and heat exchanger tubes

Design Issues

1. Development, capital and operating costs

2. Achieving self-sustaining energy cell temperature conditions during startup

3. Flow induced static and dynamic loads on energy cell tubes

4. Accommodation of thermal expansion and gas temperature rise across heat exchanger

5. High temperature design of gas cell heat exchanger vessel and internals

6. Energy cell dynamic response requirements

Energy Cell Environment

1. External pressure range

2. Temperature distribution and operating range

3. Flowrates and flow induced loads

4. Startup and control requirements

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Figure G-5 Forced Convection Closed Cycle

Gas Cell Heat Exchanger

Hydrogen Manifold
Flow Distributor Plate
Vacuum Manifold
Catalyst Manifold
Energy Cells

Turbine
Generator
Recuperator

Closed Cycle Gas Turbine-Generator

Compressor
Precooler
Clo Water Pump
Cooling Tower

Attachment F

"S-1 Radiant Recirculating Boiler" (Technology Insights).

PHI CONFIDENTIAL*

S-1 Radiant Recirculating Boiler

S-1.0 Summary

Precedents

ABB/Combustion Engineering, Foster Wheeler oil, gas and coal fired steam boilers.

Summary Description

A bank of cylindrical HydroCatalysis energy cells is positioned adjacent to a bank of boiler tubes inside an insulated container with a reflective inner surface. A movable mirror lattice between the energy cells and boiler tubes is used to control heat transfer from the energy cells during startup and power operation. The boiler circuit is a natural convection recirculating loop with a steam drum containing steam separation equipment to meet the minimum inlet steam quality requirements of the turbine.

Concept Strengths

1. Low external pressure on energy cells

2. No flow induced structural loads on energy cells

3. Control of energy cell heat losses during startup

4. Boiler tube temperature relatively constant over the tube length and over the load range

Design Issues

1. Accommodation of thermal expansion

2. Energy cell temperature variation characteristics over the load range

3. Radiant panel heat flux – size requirements

Energy Cell Environment

1. Temperature distribution and operating range

2. Startup and control requirements

Turbine Application Options

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Figure S-1 Radiant Recirculating Boiler

Steam Turbine-Generator

Generator

LP Turbine

IP Turbine

Cooling Tower

Cire Water Pump

Condensed Hotwell

Condensate Pump.

Deaerator

Feedwater Pump

Steam Drum

Boiler Tube Panel

Mirror Lattice Panel

Energy Cell Panel

Mirror Surface Insulation

Mirror Panel Actuator

Hydrogen Manifold

Catalyst Manifold

Vacuum Manifold

Gas Cell Boiler

S-1.1 Thermal Analysis

Heat transfer for the radiant concept can be approximated by neglecting convection and treating the energy cell and boiler tube panels as gray bodies. This results in radiation from the energy cell surface given by the expression:
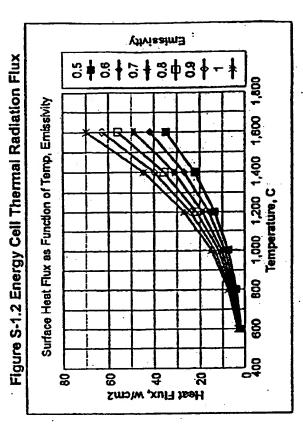
$$E_g = \epsilon_g \, \sigma T^4, \text{ where}$$

E_g = Gray body emissive power, watts/cm^2

ϵ_g = Surface emissivity

σ = Stefan-Boltzman constant = 5.675×10^{-12} watts/cm$^2 \cdot ^\circ$K^4

T = Surface Temperature, $^\circ$K

For the temperature range likely to be of interest for the energy cell panels, the resulting thermal radiation flux as a function of surface temperature and emissivity is shown in Figure S-1.2.

Calculating the exact net radiation heat transfer between the two surfaces is a complex geometric problem requiring detailed descriptions of the energy cell and boiler tube panels, the mirror lattice and chamber walls. However, to a first approximation the heat transfer can be estimated by treating the system as a 1 dimensional configuration with equivalent surface area corresponding to the frontal surface of the energy cell and boiler tube panels. Under these assumptions, the net heat transfer per unit panel frontal surface area is given by

$$E_{net} = (E_{g,1} - E_{g,2}) \, F_{1\text{-}2} = \sigma F_{1\text{-}2} \, (\epsilon_{g,1} \, T_1^4 - \epsilon_{g,2} \, T_2^4), \text{ where}$$

Subscripts 1 and 2 refer to the energy cell and boiler tube panel surfaces respectively

$F_{1\text{-}2}$ = Geometric shape factor for radiation between surfaces 1 and 2 ($F_{1\text{-}2} = F_{2\text{-}1}$ since the areas are equal)

Figure S-1.2 Energy Cell Thermal Radiation Flux

Surface Heat Flux as Function of Temp, Emissivity

Emissivity: 0.5, 0.6, 0.7, 0.8, 0.9, 1

X-axis: Temperature, C (400, 600, 800, 1,000, 1,200, 1,400, 1,600, 1,800)

Y-axis: Heat Flux, w/cm2 (0, 20, 40, 60, 80)

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A horizontal cross section of a radiant recirculating boiler concept consistent with the system diagram shown in Figure S-1.1 is shown in Figure S-1.3. In this diagram, the energy cells are assumed to be vertical tubes aligned in the center of an insulated chamber with a reflective inner surface. The boiler tubes are placed along the two walls of the chamber opposite the energy cell panel. A lattice of mirrors between the energy cells and boiler tubes would be in the open position for power operation as shown in the figure. Larger units may consist of alternating energy cell and boiler tube panels, with interior boiler tube panels receiving radiant heat from energy cell panels on both sides.

The heat transfer performance as a function of energy cell panel temperature for a representative set of conditions was estimated using the assumptions discussed on the previous page. A steam pressure of 1,000 psig was selected as a reference, with lower pressures having a negligible effect on the results. Energy cell and boiler panel emissivities of 0.9 were selected as practical, achievable values. An equivalent linear shape factor of 0.8 was selected as a reasonable and likely conservative representation of the configuration. The results show a factor of 10 variation in heat transfer over the 800-1600°C energy cell panel surface temperature range, with a maximum value of approximately 1
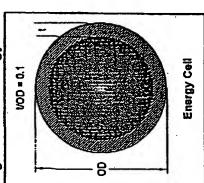
Figure S-1.3 Horizontal Cross Section

Energy Cell Panel
Mirror Lattice Panel
Boiler Tube Panel

Figure S-1.4 Boiler Performance

Power per Unit Energy Cell Panel Area
Power Operation Configuration

Panel Temperature, C

Panel Power, KW/m^2

1. Steam Pressure - 1000 psig
2. Energy cell, boiler emissivities - 0.8
3. Equivalent linear shape factor - 0.8

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Figure S-1.6 Cell Power Density

Energy Cell Power Density vs. Temperature, Energy Cell Tube Diameter, cm

1. Steam Pressure - 1000 psig
2. Panel, boiler emissivities - 0.9
3. Equivalent linear view factor - 0.8

Figure S-1.5 Energy Cell

megawatt per square meter of energy cell panel frontal surface area. The HydroCatalysis cell energy density requirements for this concept are determined by the cell interior volume per unit frontal surface area. This was estimated assuming the energy cells are in the form of cylindrical tubes with a wall thickness equal to 10% of the tube outside diameter and the reaction zone encompassing the entire interior volume, as shown in Figure S-1.5. In this configuration, the energy cell reaction zone volume per unit panel frontal area is proportional to the tube diameter. The required power density to produce the heat transfer performance shown in Figure S-1.4 was calculated as a function of energy cell tube outside diameter, with results as shown in Figure S-1.6. The heat exchanger performance and energy cell power densities shown in Figures S-1.4 and S-1.6 illustrate the inherent response characteristics of this concept. As such, they illustrate how th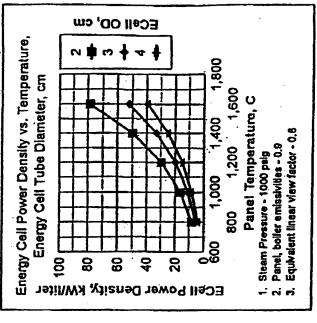e unit may operate over the load range. For example, if a minimum load of 20% of rated power were used, the energy cell panel would be brought to a temperature of approximately 1,000°C (as indicated by Figure S-1.4) to establish stable power operation at the low end of the range. Increasing the energy cell power level would result in increasing cell temperatures, reaching a maximum operating cell temperature of 1,600 °C at full rated power. Under full power conditions, the maximum surface heat flux at the boiler tubes would be approximately 500 kW/m² (half the bidirectional frontal area power of the cell panel), compared to a burnout heat flux (transition from annular to mist flow) estimated to be well in excess of 3,000 kW/m².

S-1.2 Operational Considerations

A primary operational consideration is the startup of the unit. As currently understood, the HydroCatalysis cells are expected to require an elevated temperature in the reaction zone (i.e., ~1,000°C) to achieve self-sustaining energy

production. The concept provides for thermal isolation of the energy cells from the heat sink (boiler tubes) for heatup to minimum initial temperatures. The approach, as illustrated in Figure S-1.7, is to rotate the mirror lattice panel for startup to isolate the energy cell panel in a reflective enclosure. This will substantially reduce the amount of energy required to bring the energy cells to initial operating temperature. Heating up the energy cells to self-sustaining temperatures could be accomplished either by combustion of hydrogen in the region around the boiler, or resistance heating of the energy cell panel. Combustion could be faster and cheaper, but may pose problems with fouling the mirrors, while resistance heating would be clean, but would present design problems with connecting electrical leads. Once the HydroCatalysis conditions are achieved, energy cell panel temperatures could be controlled by a combination of hydrogen and catalyst concentrations and positioning of the mirror panels. In the power operation range the mirror panels would likely be in a full open position.

The thermal analysis shows that the energy cell panel and the boiler would be essentially decoupled, with the heat losses from the energy cell panel insensitive to the boiler panel temperature. Thus the controls for the reaction process and the boiler would be effectively independent, with supervisory level control to maintain the balance of heat generation and removal. The stability of the recirculating boiler, resulting from the large water thermal mass and mixing of incoming feedwater with recirculating saturated liquid, and expected large margins to boiling limits will simplify the boiler control requirements with regard to meeting turbine load demands. The relatively small thermal mass of the energy cell panel may make for more challenging control requirements on power generation to maintain the panel within temperature limits, depending on the dynamic characteristics of the HydroCatalysis process.

S-1.3 Development Requirements

Outside the technology development required to determine the static and dynamic characteristics and limitations of the HydroCatalysis process, much of the work to be done to develop this concept would be expected to be addressing conventional engineering design issues or modifications of existing designs. The boiler tube panel would be very similar to the economizer/evaporator section of a conventional recirculating water wall fossil boiler, with less challenging environmental conditions. Boiler controls and the balance of the power conversion system should be commercially

Figure S-1.7 Boiler Configurations

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available. The energy cell panel would require considerable design development and component testing to address issues such as accommodation of high temperatures and thermal expansion; routing and valving of the hydrogen and vacuum manifolds; and routing, valving, heat tracing and partial pressure control of the catalyst manifold. Design of the energy cell controls will need to address balancing the cells for uniform power production as well as providing stable dynamic response as required by the supervisory control system and material limits of the panels. Design of the equipment and controls for heating the energy cell panel to minimum power operating conditions on startup will also require unique new design development.

S-1.4 Economic Assessment